Physics Beyond Colliders Kickoff

Chris Quigg

Fermi National Accelerator Laboratory

Fermilab Theory Seminar · 15 September 2016

Physics Beyond Colliders Kickoff Workshop
CERN · 6–7 September 2016

The aim of the workshop is to explore the opportunities offered by the CERN accelerator complex and infrastructure to get new insights into some of today's outstanding questions in particle physics through projects complementary to high-energy colliders and other initiatives in the world. The focus is on fundamental physics questions that are similar in spirit to those addressed by high-energy colliders, but that may require different types of experiments. The kickoff workshop is intended to stimulate new ideas for such projects …

Jörg Jaeckel · Mike Lamont · Claude Vallée

Mandate of the "Physics Beyond Colliders" Study Group

CERN Management wishes to launch an exploratory study aimed at exploiting the full scientific potential of its accelerator complex and other scientific infrastructure through projects complementary to the LHC and HL-LHC and to possible future colliders (HE-LHC, CLIC, FCC). These projects would target fundamental physics questions that are similar in spirit to those addressed by high-energy colliders, but that require different types of beams and experiments.

This study should provide input for the future of CERN's scientific diversity programme, which today consists of several facilities and experiments at the Booster, PS and SPS, over the period until ~2040. Complementarity with similar initiatives elsewhere in the world should be sought, so as to optimize the resources of the discipline globally, create synergies with other laboratories and institutions, and attract the international community.

Scientific goal

The main goal of the Study Group is to explore the opportunities offered by the CERN accelerator complex to address some of today's outstanding questions in particle physics through experiments complementary to high-energy colliders and other initiatives in the world. These experiments would typically: *(i)* enrich and diversify the CERN scientific program, *(ii)* exploit the unique opportunities offered by CERN's accelerator complex and scientific infrastructure, *(iii)* complement the laboratory's collider programme (LHC, HL-LHC and possible future colliders). Examples of physics objectives include searches for rare processes and very-weakly interacting particles, measurements of electric dipole moments, etc.

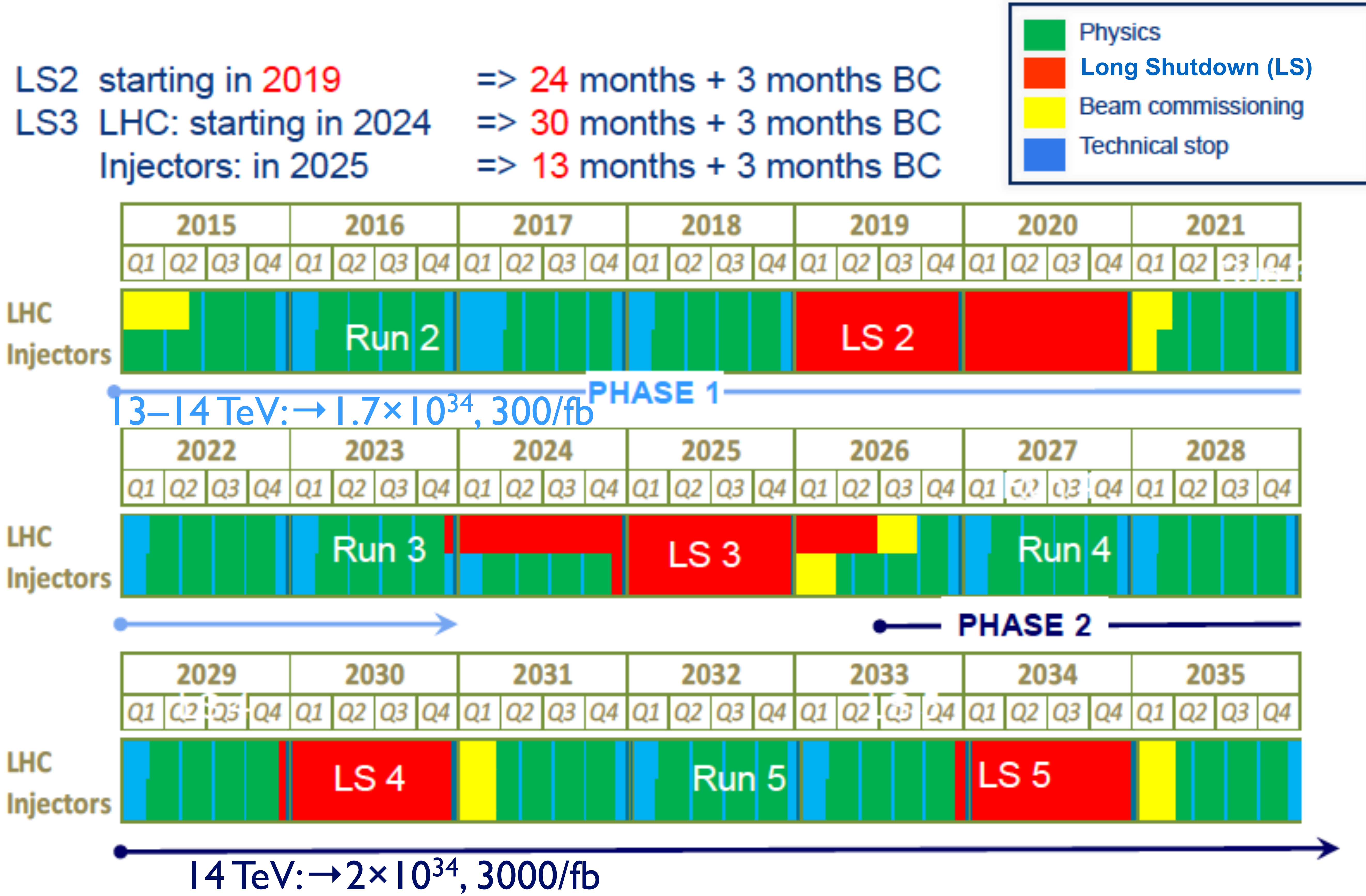
Structure of the Study Group and deliverables

The group will be led by three coordinators representing the scientific communities of accelerator, experimental, and theoretical particle physics: Joerg Jaeckel (Heidelberg), Mike Lamont (CERN), Claude Vallée (CPPM, Marseille).

Following consultation with the relevant communities, they will define the structure and the main activities of the group and appoint conveners of thematic working groups as needed. They will call a kick-off meeting in 2016, organize regular meetings, and monitor the overall scientific activity. The scientific findings will be collected in a report to be delivered by the end of 2018. This document will also serve as input to the next update of the European Strategy for Particle Physics.

CERN 20-year schedule

LS2 starting in 2019 => 24 months + 3 months BC
LS3 LHC: starting in 2024 => 30 months + 3 months BC
Injectors: in 2025 => 13 months + 3 months BC



*outline LHC schedule out to 2035 presented by Frederick Bordry to the SPC and FC June 2015

Fermilab

2013

Setting the scene

Theorists' motivations, ideas, wishes

Accelerator & infrastructure opportunities at CERN

Potential future of existing programs

New experimental ideas

Full list of submitted abstracts

Setting the Scene: DG Fabiola Gianotti

We know there is new physics.

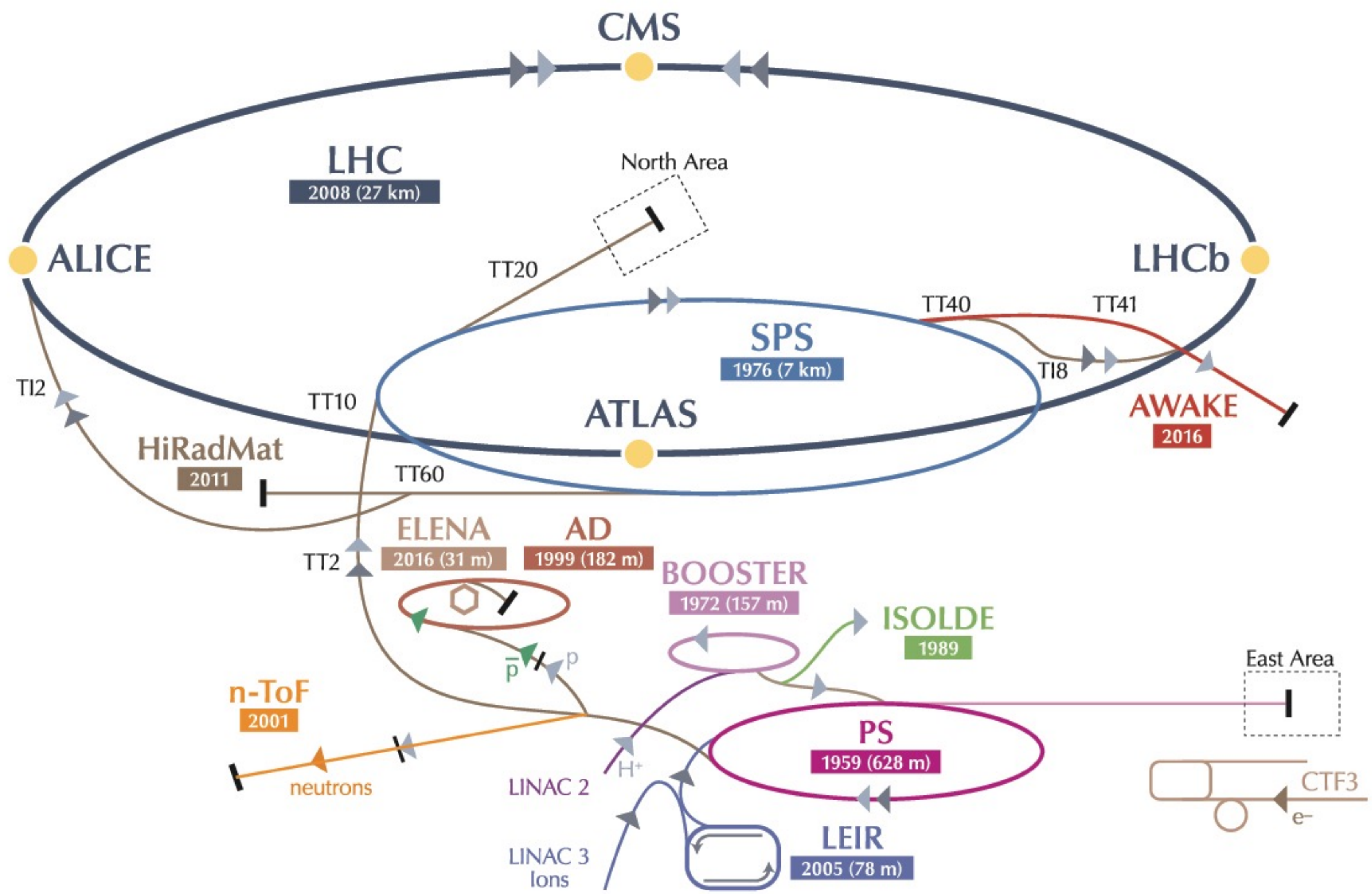
We don't know where it is.

We need to explore as broadly as possible.

Optimize the resources of the discipline globally.

« Diversity and scale diversity »

CERN Accelerator Complex



p (proton) ion neutrons p̄ (antiproton) electron proton/antiproton conversion

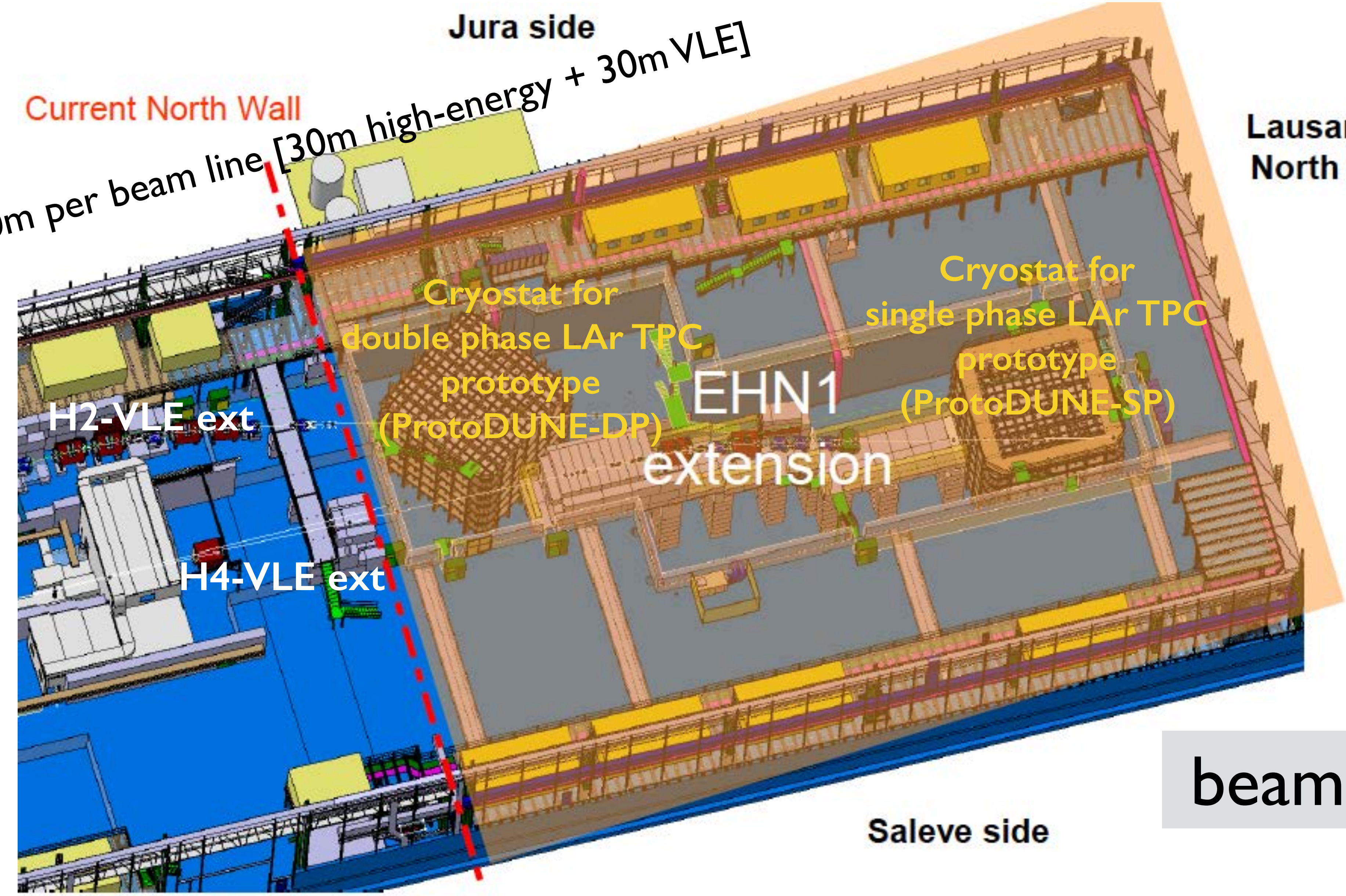
LHC Large Hadron Collider **SPS** Super Proton Synchrotron **PS** Proton Synchrotron

AD Antiproton Decelerator **CTF3** Clic Test Facility **AWAKE** Advanced WAKefield Experiment **ISOLDE** Isotope Separator OnLine DEvice

LEIR Low Energy Ion Ring **LINAC** LINear ACcelerator **n-ToF** Neutrons Time Of Flight **HiRadMat** High-Radiation to Materials

Approved Experiments reviewed by the SPS and PS Experiments Committee (SPSC), Status Sept. 2016			
Experiment		**Description**	**Comment**
AD2 (ATRAP)	AD	Precise laser or microwave spectroscopy of trapped antihydrogen	
AD3 (ASACUSA)		Atomic Spectroscopy And Collisions Using Slow Antiprotons	
AD4 (ACE)		Relative Biological Effectiveness of Antiproton Annihilation	finished data taking
AD5 (ALPHA)		Antihydrogen spectroscopy	
AD6 (AEGIS)		Testing gravity with antimatter	
AD7 (GBAR)		Testing gravity with antimatter	
AD8 (BASE)		Comparisons of the fundamental properties of antiprotons and protons	
PS212 (DIRAC)	PS	Observation of mesonic atoms and tests of low energy QCD	finished data taking
PS215 (CLOUD)		Influence of galactic cosmic rays (GCRs) on aerosols and clouds	
NA58 (COMPASS)	SPS	Study of hadron structure and hadron spectroscopy	
NA61 (SHINE)		Strong interactions, neutrinos and cosmic rays	
NA62		Measuring rare kaon decays	
NA63		Electromagnetic Processes in strong Crystalline Fields	
NA64		Search for dark sectors in missing energy events	
UA9 (CRYSTAL)		Crystal Channeling	
AWAKE		Advanced Proton-Driven Plasma Wakefield Acceleration Experiment	
WA104 (NP01)	Neutrino Facility	Refurbishment of the ICARUS Detector	
ProtoDUNE-DP (NP02)		Prototype of a Double-Phase Liquid Argon TPC for DUNE	
ProtoDUNE-SP (NP04)		Prototype of a Single-Phase Liquid Argon TPC for DUNE	
Baby MIND (NP05)		Prototype of a Magnetized Iron Neutrino Detector	
CAST	non-accel. Experiments	Search for Axions and Axion-like particles	
OSQAR		Search for QED vacuum magnetic birefringence, Axions and photon Regeneration	
CNGS1 (OPERA)	CNGS	Neutrino oscillation experiment at LNGS	finished data taking
CNGS2 (ICARUS)		Neutrino oscillation experiment at LNGS	finished data taking

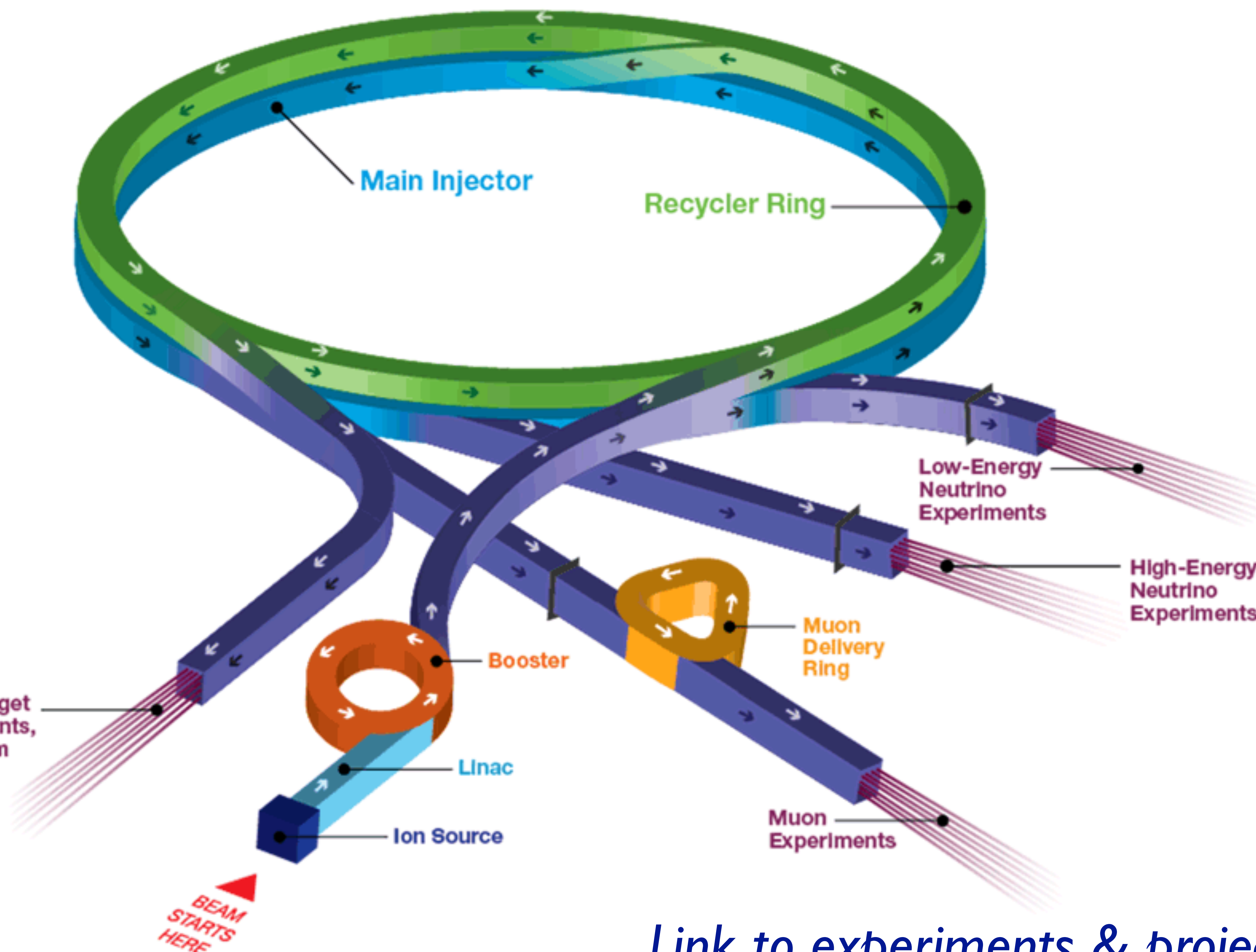
The **neutrino platform** at CERN is currently constructed to develop and prototype the next generation of neutrino Liquid Argon (LAr) detectors



beams available 2018

H2 extension: 1(0.5)÷12 GeV tertiary beam, H4 extension: 1(0.2)÷7(10)GeV tertiary beam
Beam characteristics:
Secondary beam of 80Gev (π/p, or e) produces the tertiary low−energy beams on a secondary target
VLE beams: mixed hadrons (π±, μ±, K±, p), ~pure electron (e±) beams

Fermilab Accelerator Complex



Link to experiments & projects

Theorists' motivations, ideas, wishes

M. Shaposhnikov · *New physics below the Fermi scale*

M. Pospelov · *EDMs & precision $(g-2)_\mu$*

A. Ringwald · *Axions, ALPs: Astro/cosmo motivations & tests*

C. Burrage · *Detecting dark energy with atom interferometry*

P. Graham · Precision measurement for particle physics

The LHC results must be reconciled with the evidence for new physics beyond the Standard Model:

- Observations of neutrino oscillations (in the SM neutrinos are massless and do not oscillate)
- Evidence for Dark Matter (SM does not have particle physics candidate for DM).
- No antimatter in the Universe in amounts comparable with matter (baryon asymmetry of the Universe is too small in the SM)
- Cosmological inflation is absent in canonical variant of the SM
- Accelerated expansion of the Universe (?) - though can be "explained" by a cosmological constant.
- Marginal evidence (less than 2σ) for the SM vacuum metastability given uncertainties in relation between Monte-Carlo top mass and the top quark Yukawa coupling

Energy scale of new physics from experiment or theory:

- Neutrino masses and oscillations: the masses of right-handed see-saw neutrinos can vary from $\mathcal{O}(1)$ eV to $\mathcal{O}(10^{15})$ GeV
- Dark matter, absent in the SM: the masses of DM particles can be as small as $\mathcal{O}(10^{-22})$ eV (super-light scalar fields) or as large as $\mathcal{O}(10^{20})$ GeV (wimpzillas, Q-balls).
- Baryogenesis, absent in the SM: the masses of new particles, responsible for baryogenesis (e.g. right-handed neutrinos), can be as small as $\mathcal{O}(10)$ MeV or as large as $\mathcal{O}(10^{15})$ GeV
- Higgs mass hierarchy : models related to SUSY, composite Higgs, large extra dimensions require the presence of new physics right above the Fermi scale , whereas the models based on scale invariance (quantum or classical) may require the absence of new physics between the Fermi and Planck scales

Hidden particles: νSM as example

SM: $d_e < 10^{-37}$ ecm, $d_n < 10^{-31}$ ecm

EDMs and New Physics

- EDM observable ~

  ~ [some QCD/atomic/nuclear matrix elements] ×

SM mass scale (m_e, m_q) × $(\text{CP phase})_{NP}/\Lambda_{NP}^2$

With some amount of work all matrix elements can be fixed. For the flavor blind NP, $d_i \sim m_i$. Unfortunately, we have no idea where actually Λ_{NP} is !!!

100 GeV, 1 TeV, 10 TeV, 100 TeV, 1000 TeV … GUT scale … M_P

After the LHC did not find the abundance of new states immediately above EW scale, "guessing EDMs" became even more difficult. *What shall we put in the denominator*? E.g. $(\text{TeV})^2$ or $(\text{PeV})^2$?

New physics in $(g\text{–}2)_\mu$

The New Physics contribution could be $\sim a_\mu^{NP} = (26.1\pm8)\times10^{-10}$.

This is ~ twice the size of the SM electroweak contribution, and in these units *not small*.

Weak scale solutions.

Main challenges are to create such a large shift of a_μ and stay undetected at LEP, Tevatron and LHC experiments

Sub-GeV scale solutions.

These must be additional electrically *neutral* states, with small couplings to normal matter that somehow escape detection

Many PBC opportunities

Axions & ALPs: astrophysical hints

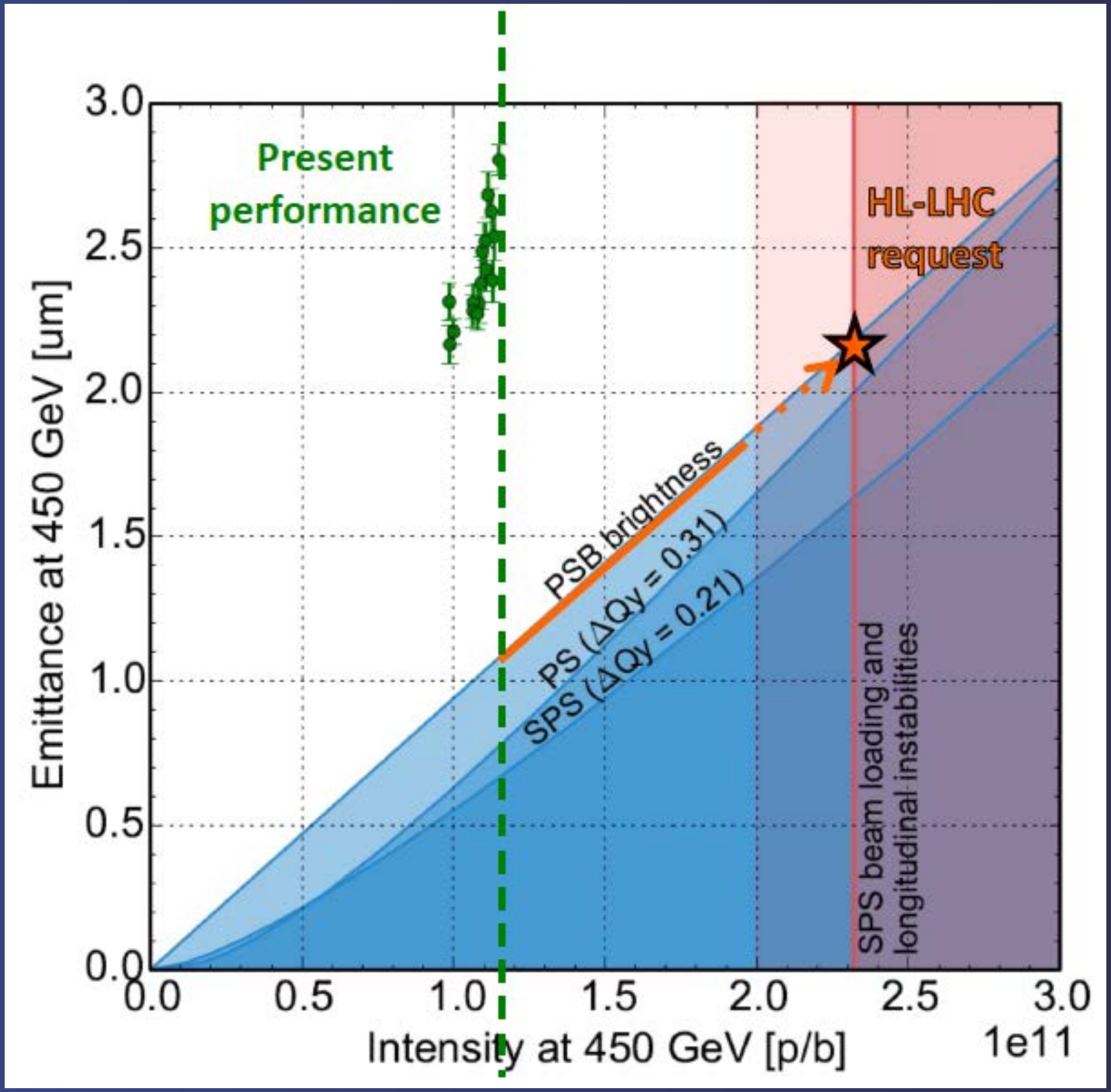
Excess energy loss in stars
= ALP emission?
Anomalous gamma transparency
= photon–ALP conversion in magnetic fields?

Accelerator & infrastructure opportunities at CERN

G. Rumolo · *Proton throughput (injector upgrades)*
L. Gatignon · *Beams in North & East Areas*
M. Calviani · *SPS beam dump facility*
M.A. Fraser · *SPS slow extraction*
A. Lombardi · *Proton drivers*
S. Redaeli · *Multi-TeV beam channeling …*
W. Scandale · *Bent-crystal baryon magnetic moment*
M. Bai · *EDM options*
K. Long · *nuSTORM*

LHC Injector Upgrades

Goal for LS2: double brightness and intensity of LHC beams (<0.1% of proton delivery through HL-LHC)



LHC Injector Upgrades

Goal for LS2: double brightness and intensity of LHC beams (<0.1% of proton delivery through HL-LHC)

LHC	3×10^{17} *p*/y
SPS Beam Preparation	$\gtrsim 3\times10^{17}$ *p*/y
nTOF	1.9×10^{19} p/y
Antiproton area	2–4×10^{18} *p*/y
East area	10^{18} *p*/y
HiRadMat	2×10^{16} *p*/y
AWAKE	10^{17} *p*/y
Beam Dump Facility (355 kW)	4×10^{19} *p*/y
North Area Beams	10^{19} *p*/y

Novel μ source? 45-GeV e^+ on plasma target ⟶ 20-GeV μ

TUPMY001 Proceedings of IPAC2016, Busan, Korea

VERY LOW EMITTANCE MUON BEAM USING POSITRON BEAM ON TARGET

M. Antonelli, M. Biagini, M. Boscolo, A. Variola INFN/LNF, Frascati, Italy
P. Raimondi, ESRF Grenoble, France
G. Cavoto INFN Roma, Italy E. Bagli INFN Ferrara, Italy

Abstract

Muon beams are customarily obtained via K/π decays produced in proton interaction on target. In this paper we investigate the possibility to produce low emittance muon beams from electron-positron collisions at centre-of-mass energy just above the $\mu^+\mu^-$ production threshold with maximal beam energy asymmetry, corresponding to a positron beam of about 45 GeV interacting on electrons on target. Performances on both amorphous and crystal target are presented, and the general scheme for the muon production will be given. We present the main features of this scheme with a first preliminary evaluation of the performances that could be achieved by a multi-TeV muon collider. The very small emittance could allow high luminosity with modest muon fluxes reducing both the machine background in the experiments and more importantly the activation risks due to neutrino interactions.

MUON PRODUCTION

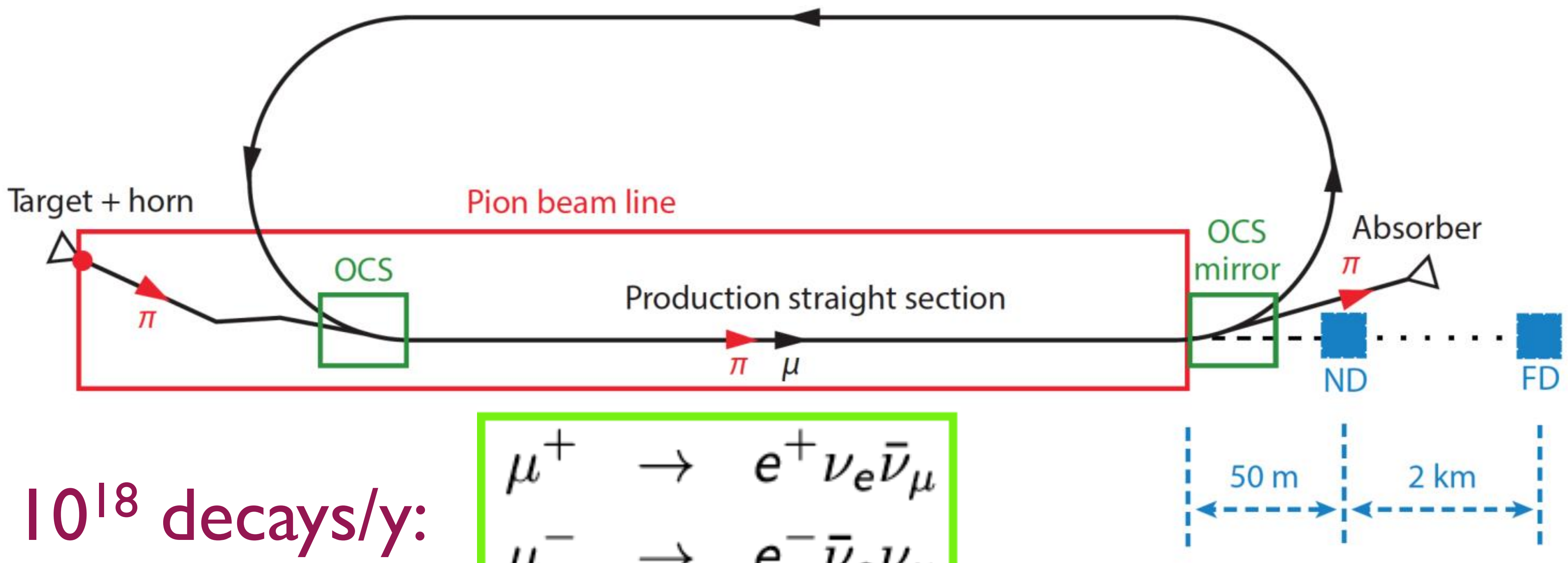
The cross section f...

tion ...

	positron source	proton source
μ rate[Hz]	$9 \cdot 10^{10}$	$2 \cdot 10^{13}$
μ/bunch	$4.5 \cdot 10^{7}$	$2 \cdot 10^{12}$
normalised ϵ [μm-mrad]	40	25000

... electron ... $\sqrt{s} \approx$. $\sqrt{s}/(2m_e) \approx 220$. The ... scattering angle of the outcoming muons θ_μ^{max}

nuSTORM overview



10^{18} decays/y:

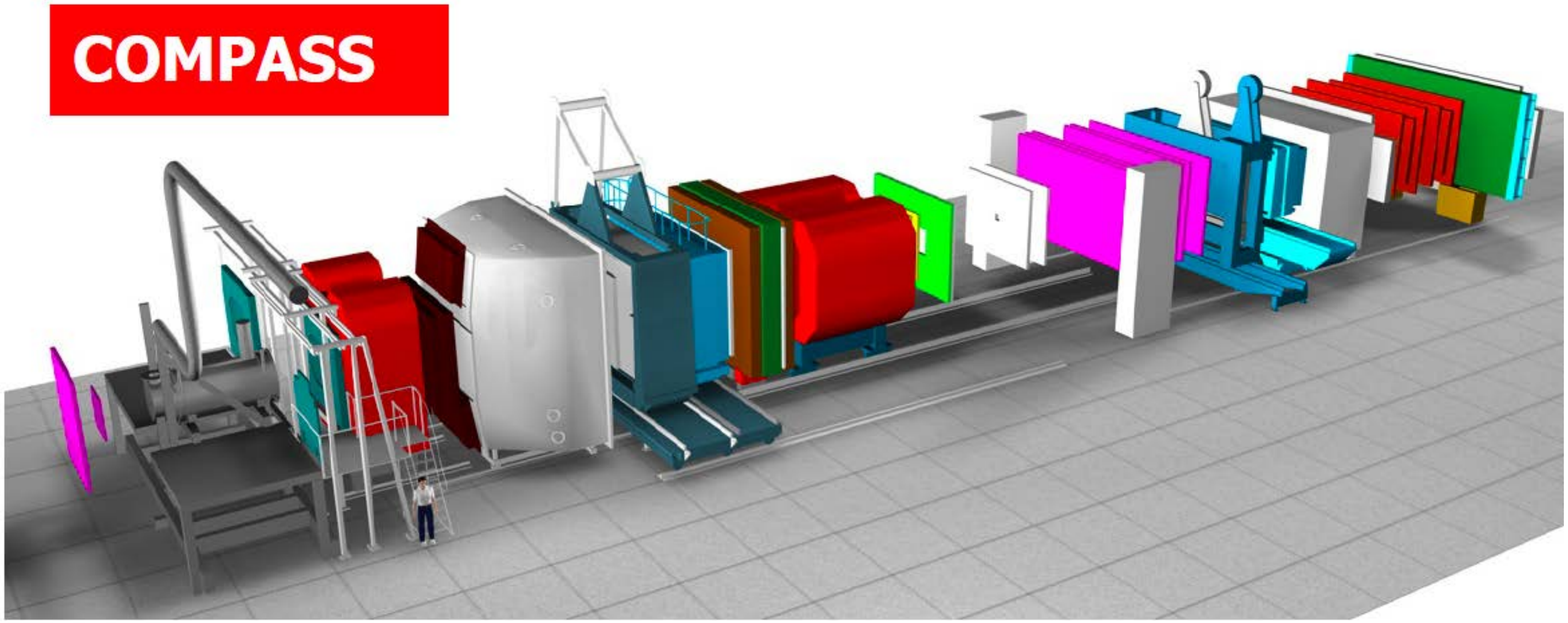
$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$
$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

- Fast extraction at >~ 100 GeV from:
  - Main Injector at FNAL or SPS at CERN
- Conventional pion production and capture (horn)
  - Quadrupole transport of pions to decay ring
- "Stochastic injection" in "orbit combination section"
  - 52% pions decay to muons before first arc
- Neutrino flux:
  - ν_μ flash from pions (and kaons) passing through injection straight
  - ν_μ and ν_e from muons; around 30 turns in one "lifetime"

Potential future of existing programs

O. Denisov · *COMPASS: hadron structure & spectroscopy*
M. Gazdzicki · *NA61: SHINE beyond 2020*
T. Spadaro · *Perspectives from NA62 (K decay)*
S. Ulmer · *Fundamental physics with antimatter*
K. Blaum · *Probing the standard model with radionuclides*

COMPASS Spectrometer at SPS M2 beam line (CERN)



Universal and flexible apparatus.
Most important features of the two-stage COMPASS Spectrometer:

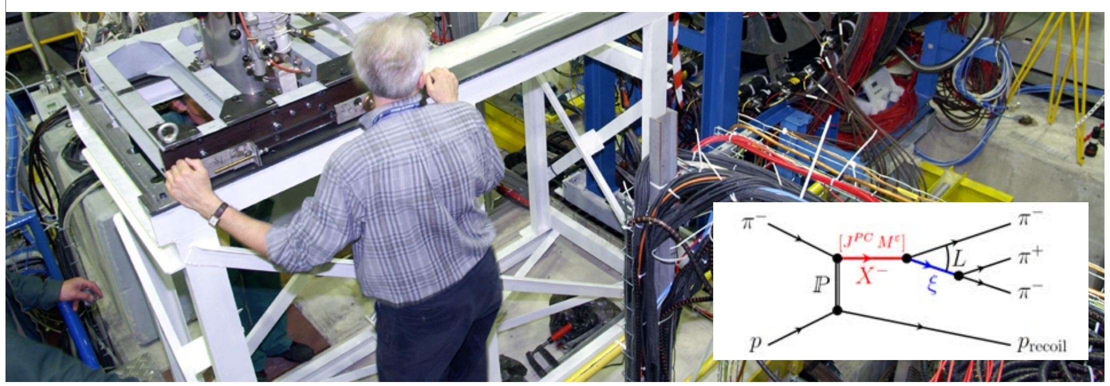
1. Muon, electron or hadron beams with the momentum range 20-250 GeV and intensities up to 10^8 particles per second
2. Solid state polarised targets (NH_3 or ^{6}LiD) as well as liquid hydrogen target and nuclear targets
3. Advanced tracking (350 planes) and powerful PiD systems (Muon Walls, Calorimeters, RICH), new DAQ

Long term plans

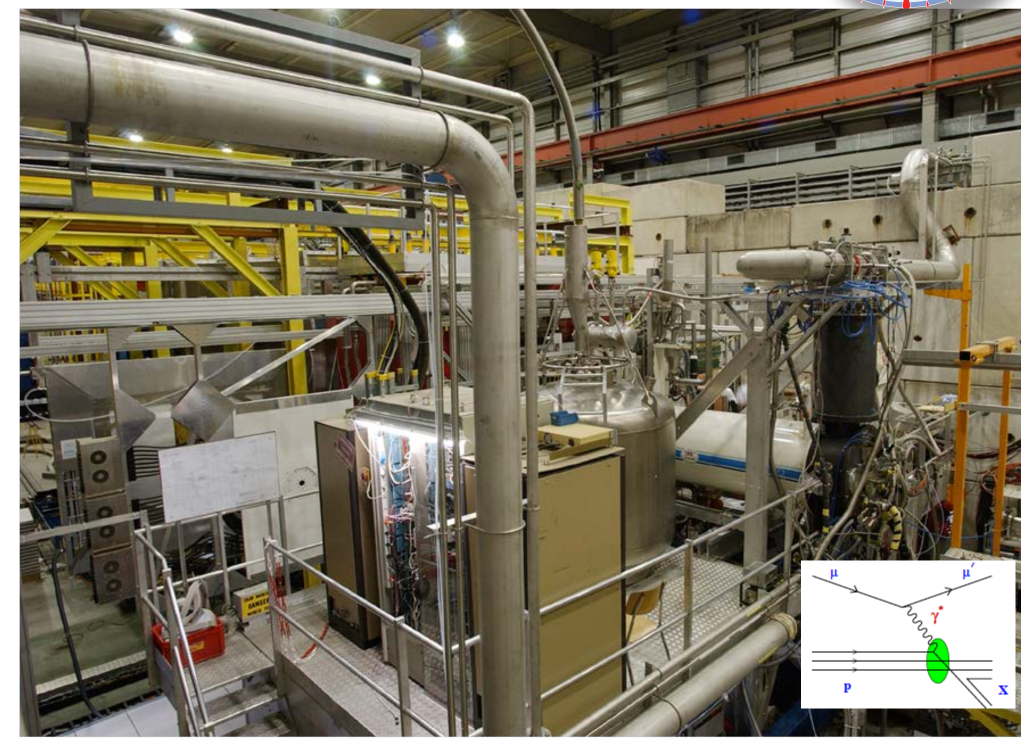
- RF separated beam
- Spectroscopy
- Drell-Yan
- Exclusive measurements with muon and hadron beams

COMPASS QCD facility at SPS M2 beam line (CERN) (secondary hadron and lepton beams)

Exotic state, chiral dynamics



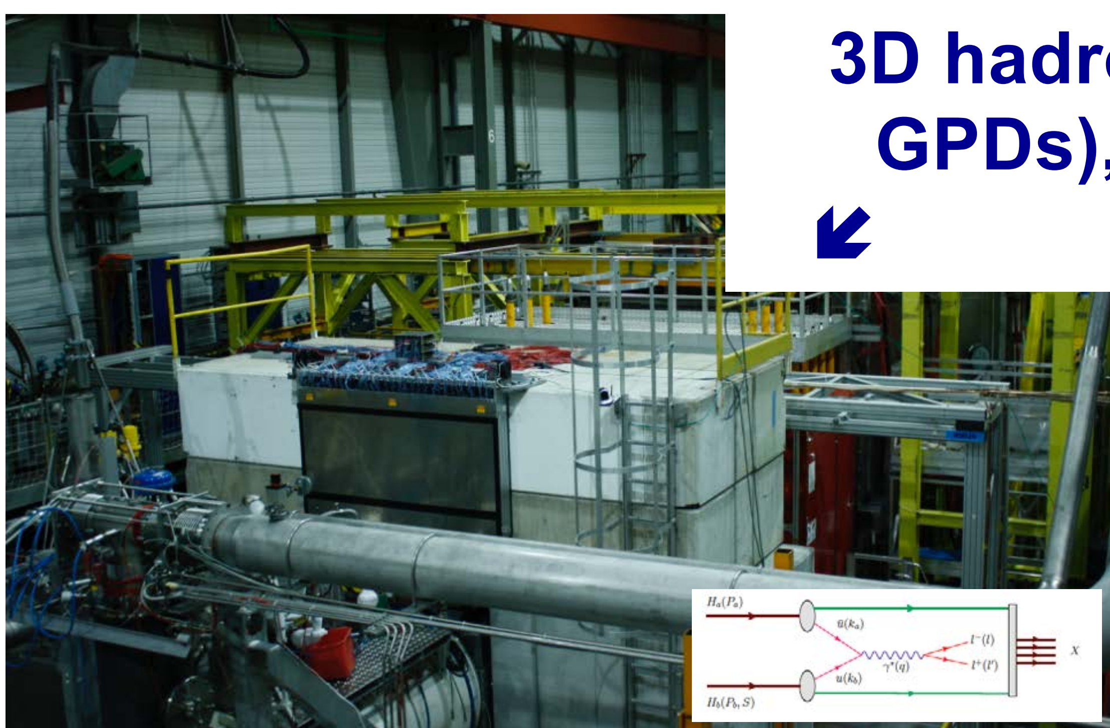
COMPASS-I
1997-2011



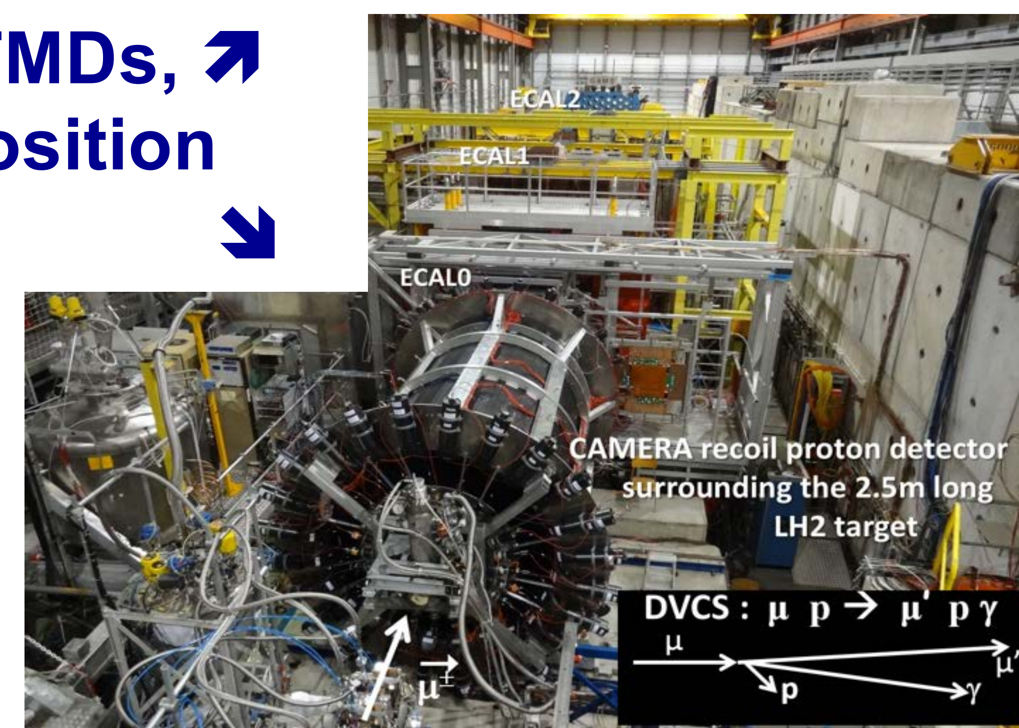
Hadron Spectroscopy & Polarisability

Polarised SIDIS

3D hadron structure (TMDs, GPDs), spin decomposition



COMPASS-II
2012-2018



Polarised Drell-Yan

DVCS (GPDs) + unp. SIDIS

SPS Heavy-Ion and Neutrino Experiment

NA61/SHINE: PHYSICS AND FACILITY

NA61/SHINE - UNIQUE MULTIPURPOSE FACILITY FOR MEASURMENTS OF HADRON PRODUCTION IN h+p, h+A AND A+A INTERACTIONS AT 13A - 150A (400) GEV/c

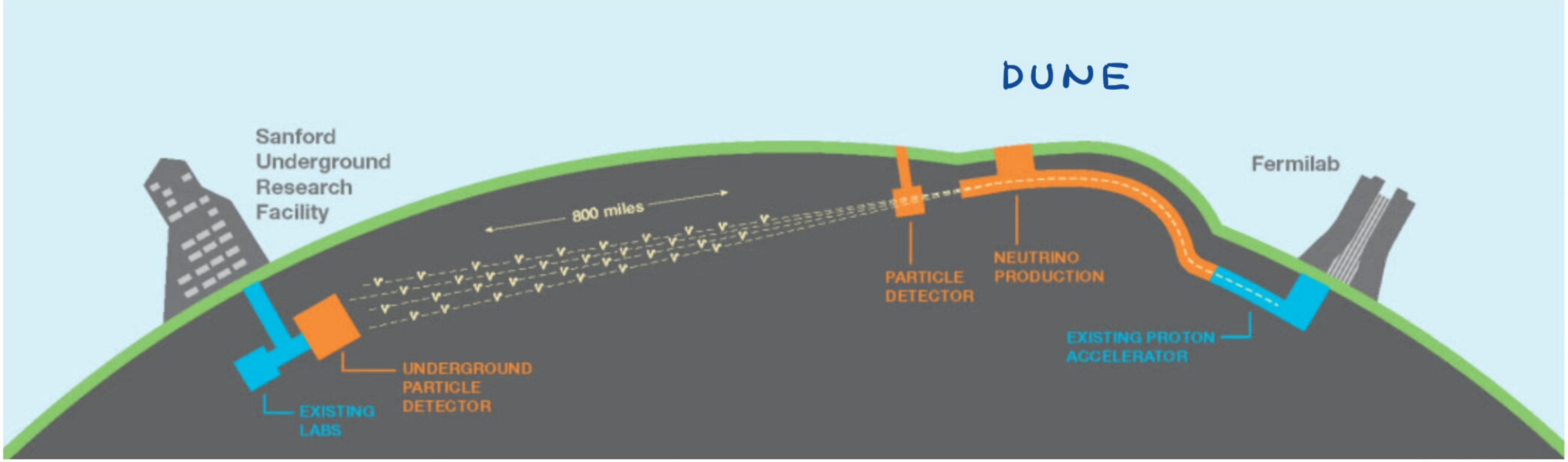
APPROVED DATA TAKING PROGRAMME (2009-2018) COVERS MEASURMENTS FOR PHYSICS OF

- STRONG INTERACTIONS
- NEUTRINOS
- COSMIC-RAYS

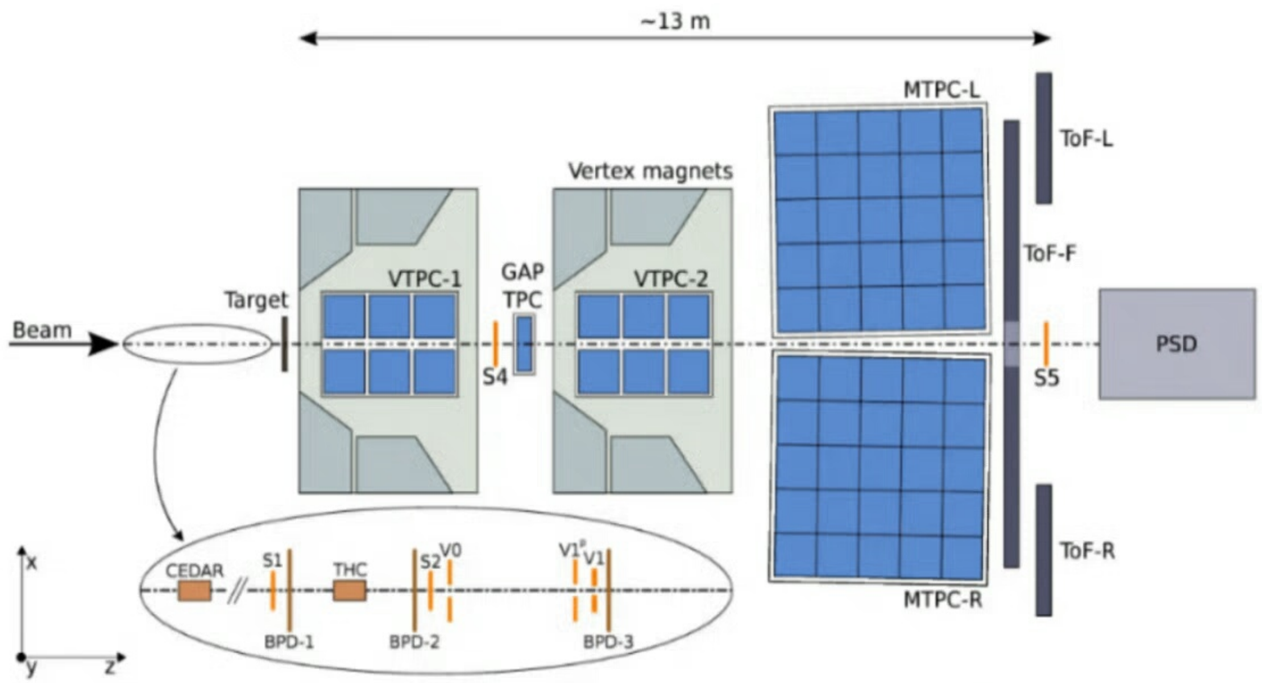
PHYSICS: NEUTRINOS

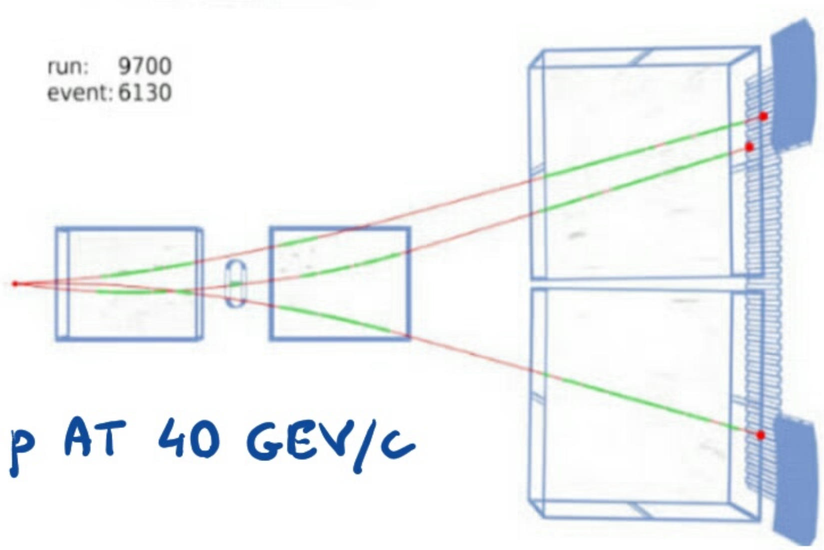
- HADRON PRODUCTION MEASUREMENTS FOR T2K
  DATA TAKING: COMPLETED
  ANALYSIS: ALMOST COMPLETED

- HADRON PRODUCTION MEASUREMENTS FOR FERMILAB NEUTRINO BEAMS
  DATA TAKING: STARTS NOW
  ANALYSIS: TO BE STARTED



SHINE FACILITY: DETECTOR





p+p AT 40 GEV/c

- A LARGE ACCEPTANCE (≈ 50%) HADRON SPECTROMETER
- BEAM PARTICLES MEASURED BY COUNTERS AND MWPCs
- CHARGE PARTICLES MEASURED BY 5 (+2) TPCs
- PID VIA dE/dx IN TPCs AND tof IN 3 ToF DETECTORS
- ENERGY OF PROJECTILE SPECTATORS MEASURED IN PSD
- PRECISE VERTEXING VIA SMALL ACCEPTANCE VERTEX DETECTOR

JINST 9 (2014) P06005

NA62: rare *K* decays

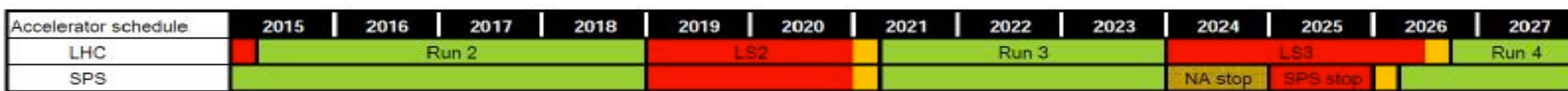
Introduction

NA62 experiment approved to run until LS2

- **main goal**: measuring the BR($K^+ \rightarrow \pi^+ \nu$ anti-ν) with 10% accuracy;
- a broad physics program: searches for LFV/LNV modes, hidden sector particles

Present talk covers possible plans for dedicated searches in **Run3**

Current Run **Run3** **Run4**



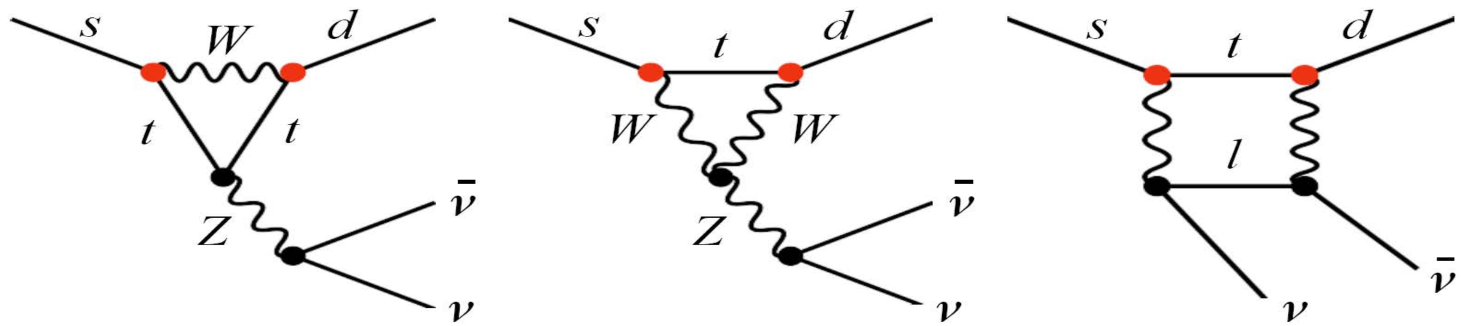
LS2 **LS3**

NA62: $K^+ \rightarrow \pi^+ \nu \nu$,
LNV/LFV decays,
hidden sector searches
in kaon decays

This talk

NA62 experiment: the goal

K → $\pi\nu\bar{\nu}$ decays: FCNC *s*--*d* loops, theoretically clean, sensitive to various NP models



SM prediction [Buras et al. arXiv:1503.02693, Brod, Gorbahn, Stamou, Phys.Rev.D 83, 034030 (2011)]:

$$\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}) = (8.39 \pm 0.30)\cdot 10^{-11}\left(\frac{|V_{cb}|}{0.0407}\right)^{2.8}\left(\frac{\gamma}{73.2°}\right)^{0.74} = (8.4 \pm 1.0)\cdot 10^{-11}$$

$$\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu}) = (3.36 \pm 0.05)\cdot 10^{-11}\left(\frac{|V_{ub}|}{0.00388}\right)^{2}\left(\frac{|V_{cb}|}{0.0407}\right)^{2}\left(\frac{\sin\gamma}{\sin 73.2}\right)^{2} = (3.4 \pm 0.6)\cdot 10^{-11}$$

Experimental status:

$\mathrm{BR}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu}) = \left(17.3^{+11.5}_{-10.5}\right)\times 10^{-11}$ Phys. Rev. D 77, 052003 (2008), Phys. Rev. D 79, 092004 (2009)

$\mathrm{BR}(\mathrm{K_L} \to \pi^0\nu\bar{\nu}) < 2.6\times 10^{-8}$ (90% C. L.) Phys. Rev. D 81, 072004 (2010)

NA62 goal: measure BR($K^+ \to \pi^+\nu\bar{\nu}$) with O(10%) total uncertainty

Physics at NA62 in Run 3

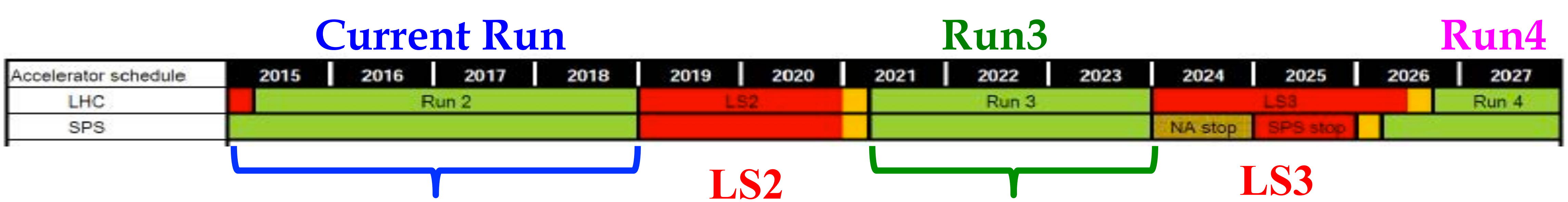
A rich field to be explored with minimal/no upgrades to the present setup

1. Present setup for K^+ beam + dedicated triggers: complete LFV/LNV high-sensitivity studies based on K^+/π^0:

$K^+ \to \pi^+\mu^\pm e^\mp$, $K^+ \to \pi^-\mu^+ e^+$, $K^+ \to \pi^- e^+ e^+$, $K^+ \to \pi^-\mu^+\mu^+$ (+ radiative modes)

$\pi^0 \to \mu e$, 3γ, 4γ, ee, $eeee$

2. Year-long run in "beam-dump" mode, new program of NP searches for MeV-GeV mass hidden-sector candidates: Dark photons, Heavy neutral leptons, Axions/ALP's, etc.



NA62: $K^+ \to \pi^+ \nu \nu$, LNV/LFV decays, hidden sector searches in K decays

LFV/LNV @ ultimate sensitivity, hidden sector searches (beam dump)

Fundamental Physics with Antimatter

Representing the AD Community

THE ALPHA COLLABORATION

Aarhus University, Denmark · University of British Columbia, Canada · University of California Berkeley, USA · University of Calgary, Canada · Imperial College London · University of Liverpool, UK · University of Manchester, UK · NRCN - Nuclear Res. Center Negev, Israel · Purdue University, West Lafayette, USA · Federal University of Rio de Janeiro, Brazil · Stockholm University, Sweden · Simon Fraser University, Canada · TRIUMF, Canada · University of Wales Swansea, UK · Cockcroft Institute, UK · York University, Canada

ATRAP Collaboration

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AEḡIS collaboration

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BASE: K. Blaum, Y. Matsuda, C. Ospelkaus, W. Quint, J. Walz, Y. Yamazaki

ALPHA · ASACUSA · BASE · ATRAP · GBAR · AEgIS

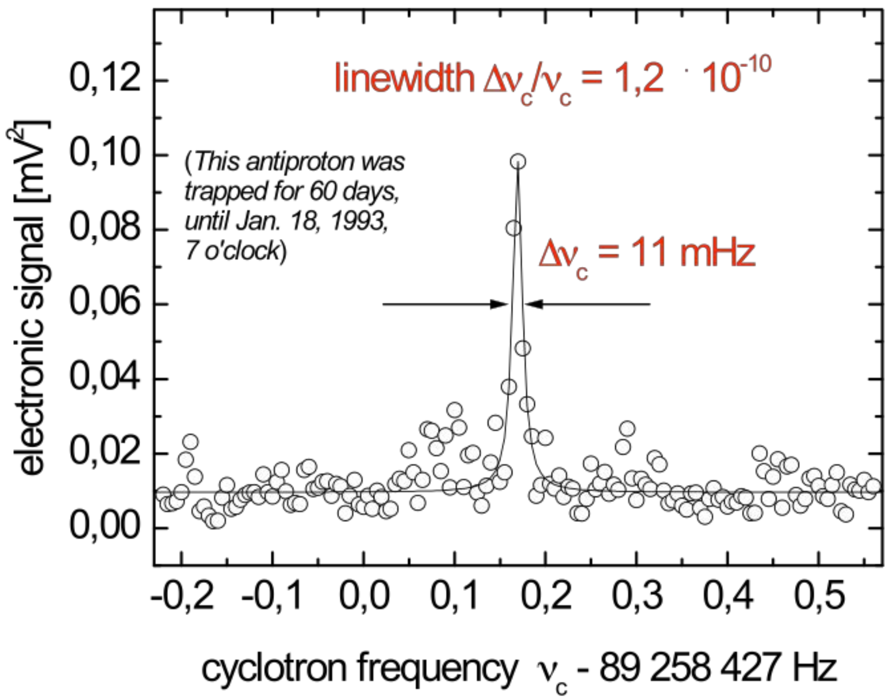
60 Research Institutes/Universities – 339 Researchers – 6 Collaborations

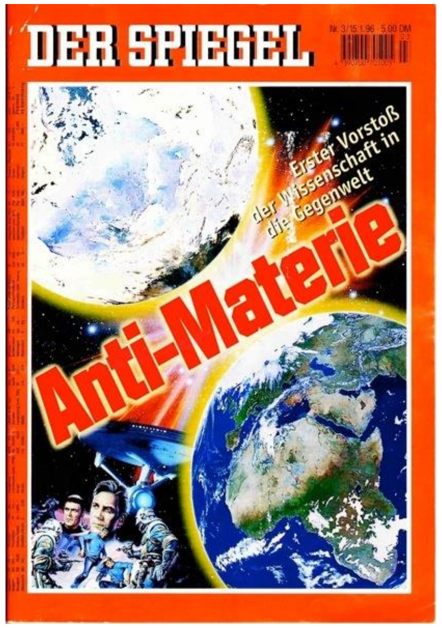
CPT tests, equivalence principle, anti-H spectroscopy

Pioneering Highlights

Production of 11(2) relativistic antihydrogen atoms at LEAR (PS210) in 1995.

G. Baur et al., Phys. Lett. B 368 (1996) 251





Comparison of the proton to antiproton charge to mass ratio at fractional precision of 90 p.p.t.

$$\frac{Q_{\bar{p}}}{M_{\bar{p}}} \Big/ \frac{Q_p}{M_p} = -0.999'999'999'91(9)$$

G. Gabrielse et al., Phys. Rev. Lett. 82 (1999) 3198

ALPHA

BASE

ATRAP

GBAR

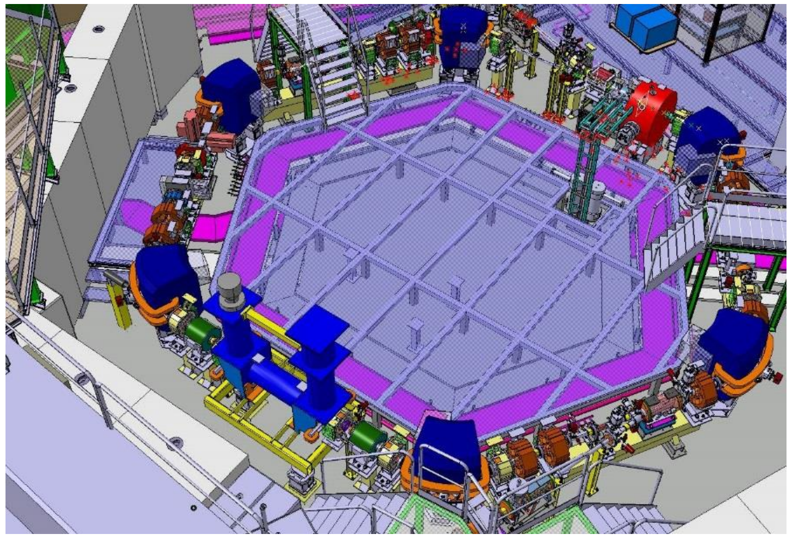
AEgIS

Convinced CERN to start the AD program.

Extra Low-Energy Antiproton Ring

ELENA

- Antiprotons are caught in Penning traps using degraders – 99.9% of particles are lost.
- ELENA provides antiprotons decelerated to 100keV – compared to the AD – at improved beam emittance.
- Degrading at low particle energies is much more efficient



Experiment	ELENA Gain Factor
ALPHA	100
ATRAP	100
ASACUSA	10
AEgIS	100

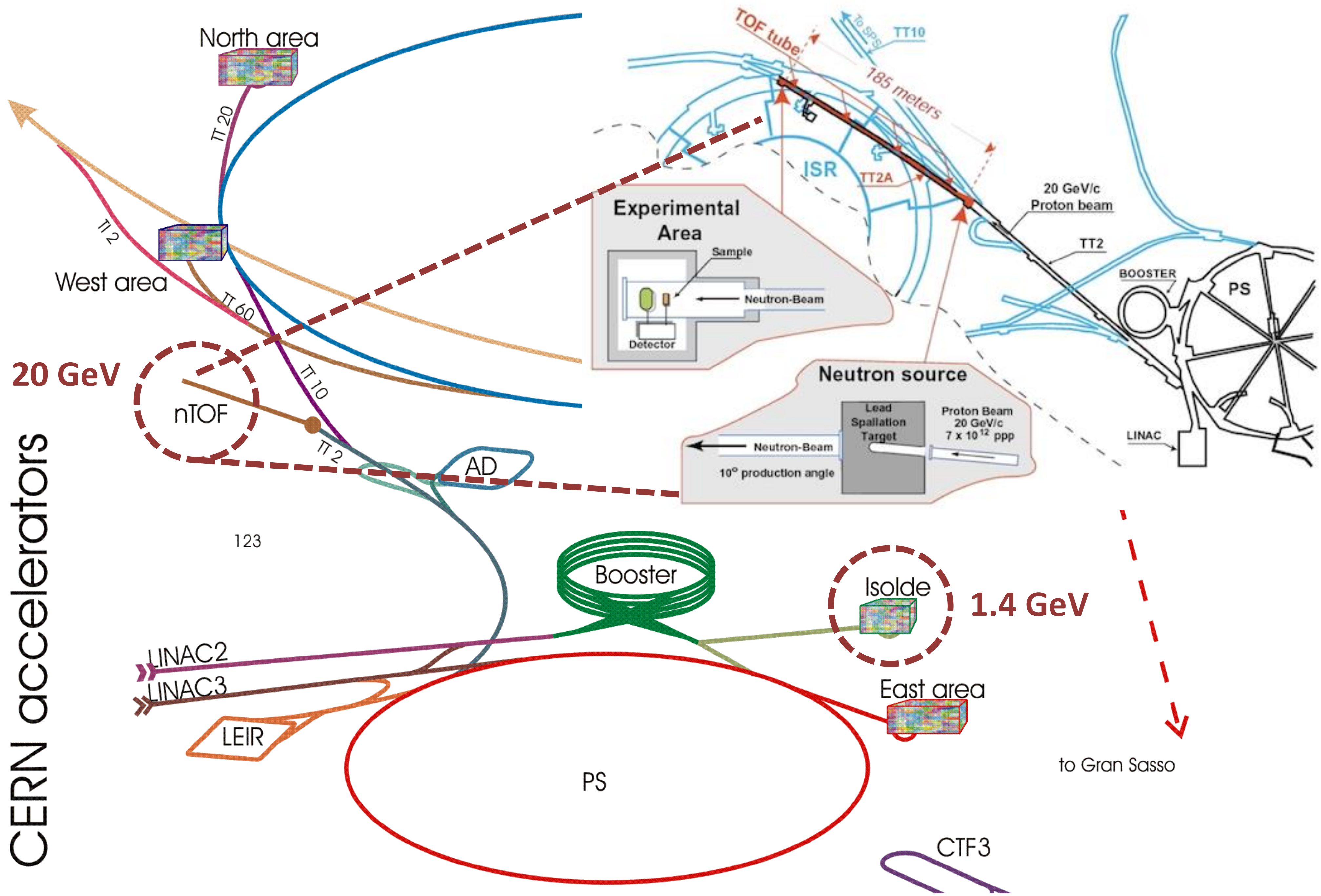
- **ELENA will be able to deliver beams almost simultaneously to all experiments resulting in an essential gain in total beam time for each experiment. This also opens up the possibility to accommodate an extra experimental zone**

ALPHA
BASE
ATRAP
GBAR
AEgIS

Provides bright future perspective for antiproton-physics at CERN

Standard-model tests with radionuclides

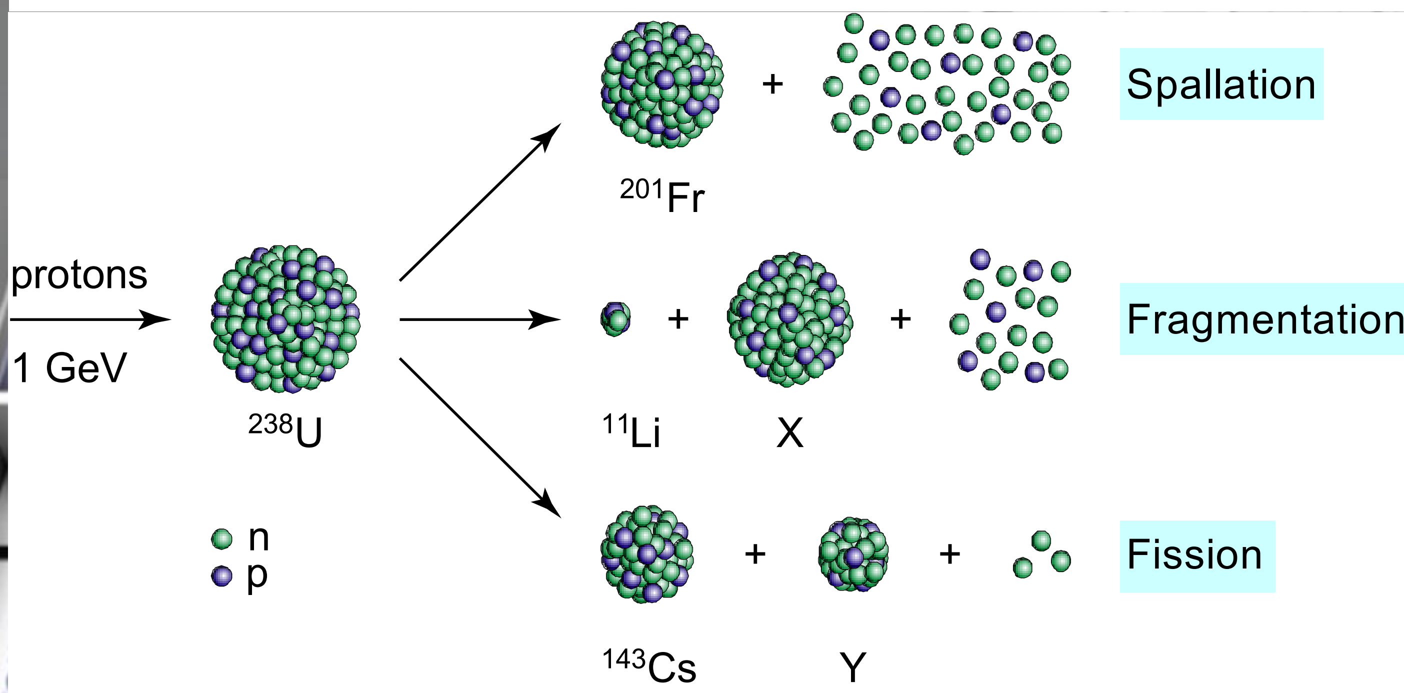
Locations

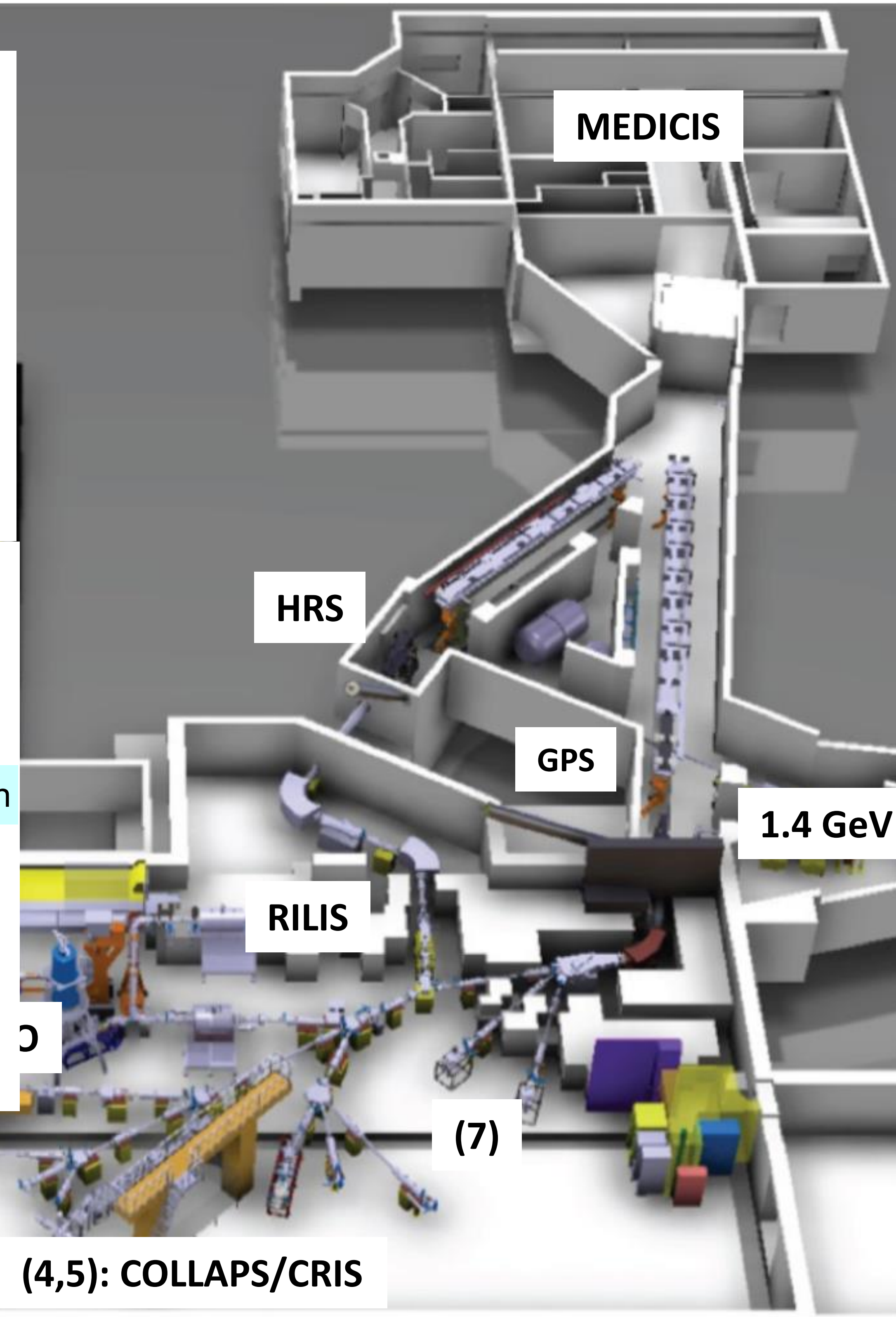


The ISOLDE radioactive beam facility

(1) Decay spectroscopy
(2) Coulomb excitation
(3) Transfer reactions
(4) Laser spectroscopy
(5) Beta-NMR
(6) Penning traps
(7) Applications:
- Solid state
- Life Sciences

>500 users, about 100 institutions, >800 isotopes





Radionuclides for the standard model and beyond

CKM unitarity test through superallowed β-decay

V_{ud} *(nuclear β-decay) = 0.97417(21)*

$|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2=0.99978(55)$

ν mass in ^{163}Ho *electron capture*

EDM search in (pear-shaped) ^{255}Ra

New Experimental Ideas

A. Golutvin · Search for Hidden Particles

S. Gninenko · NA64: Dark sector in missing-energy events

T. Bowcock · Proton EDM

M. Moulson · $K_L \rightarrow \pi^0 \nu \bar{\nu}$ (NA62 evolution)

G.Venanzoni · Hadronic corrections to a_μ by μe scattering

L. Nemenov · Dimeson atoms (π,K)–(π,K)

G. Usai · QCD phase transitions with dileptons

M.W. Krasny · The Gamma Factory Initiative

J.-P. Lansberg · AFTER: TeV fixed-target beams

A. Stocchi · Crystals for short-lived baryon magnetic moments

M.Wing · AWAKE

The SHiP experiment at SPS

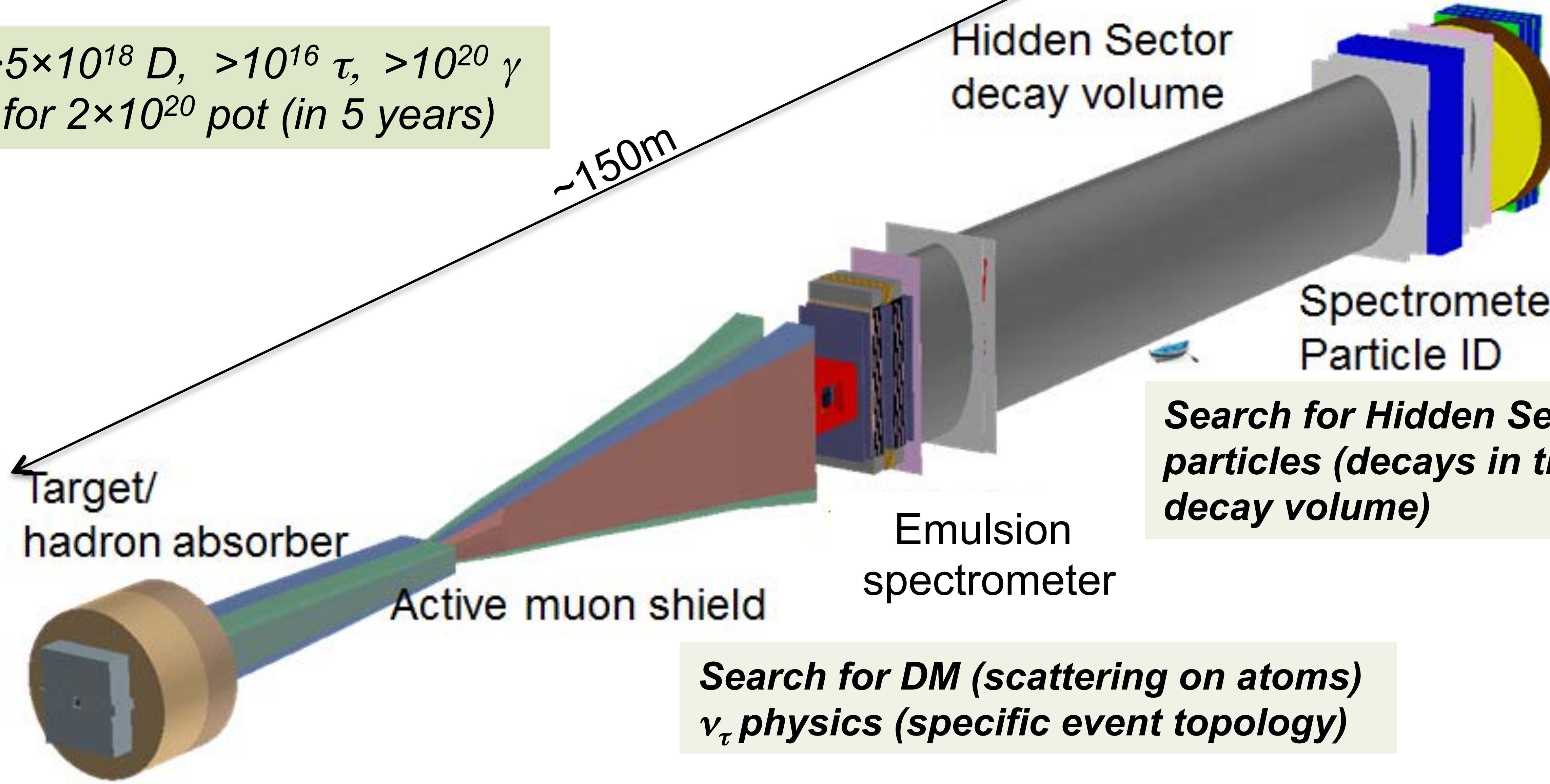
(as implemented in Geant4 for TP)

SHiP Technical Proposal:
1504.04956

"Zero background" experiment

- *Muon shield*
- *Surrounding Veto detectors*

$>5\times10^{18}$ D, $>10^{16}$ τ, $>10^{20}$ γ
for 2×10^{20} pot (in 5 years)



Search for Hidden Sector particles (decays in the decay volume)

Search for DM (scattering on atoms)
ν_τ physics (specific event topology)

Hope approval 2020, begin running 2026

NA64 : Dark sector through missing energy
(active beam dump)

Dark photons: invisible or e^+e^-

L_μ–L_τ gauge boson in μ beam

π, *K*, *p* beams to invisible decays

First run October 2016

p electric dipole moment storage ring

nEDM measured to be small .

EDMs	10^{-26} e cm	Technique	Arxiv
proton	$\|d_p\| < 79$	From ^{199}Hg	0901.2328
proposal	$< 10^{-3}$	srEDM (I)	1502.04317v1
neutron	$\|d_n\| < 2.9$		1509.04411
deuteron	$< 10^{-3}$	srEDM(II)	1201.5773

This implies a very small $\bar{\theta}$

$$\bar{\theta} \leq 2 \times 10^{-10} \longrightarrow \bar{\theta} \leq 3 \times 10^{-14}$$

Proposal to improve by orders of mag

Axions ? ..

pEDM is more than an order of magnitude more sensitive than current nEDM plans

All-electric storage ring; magic momentum 0.7 GeV

KLEVER: $K_L \to \pi^0 \nu \bar{\nu}$ at the SPS

Can a competitive measurement of BR($K_L \to \pi^0 \nu \bar{\nu}$) be made at the SPS?

NA62-16-03

Status report on design studies for an experiment to measure BR($K_L \to \pi^0 \nu \bar{\nu}$) at the CERN SPS

A. Bradley, M.B. Brunetti, F. Bucci, A. Cassese, N. Doble, D. Di Filippo, E. Gamberini, L. Gatignon, A. Gianoli, E. Imbergamo, M. Lenti, S. Martellotti, A. Mazzolari, M. Moulson[1], I. Neri, F. Petrucci, P. Rubin, R. Volpe

April 27, 2016

Interesting features:

- High-energy experiment: Complementary approach to KOTO
- Photons from K_L decays boosted forward
    - Makes photon vetoing easier - veto coverage only out to 100 mrad
- Possible to re-use LKr calorimeter, NA62 experimental infrastructure?

Summary and outlook

1. **Flavor will play an important role in identifying new physics, even if NP is found at the LHC**

New physics found at LHC

Explore flavor structure of "new" SM

Obtain **precision information** from measurements of $K \to \pi\nu\bar{\nu}$

No new physics from LHC

Explore extremely high mass scales with indirect probes

$\boldsymbol{K \to \pi\nu\bar{\nu}}$ **uniquely sensitive**

2. **NA62 and KOTO Step 1 results will arrive within next few years**

NA62/KOTO obtain unexpected results

Precise measurement of BR($K_L \to \pi^0\nu\bar{\nu}$) **extremely interesting**

NA62/KOTO obtain SM results

BR($K_L \to \pi^0\nu\bar{\nu}$) ~ (0.5 – 2) SM not excluded: precise measurement **may still reveal NP**

3. **An experiment to measure BR($\boldsymbol{K_L \to \pi^0\nu\bar{\nu}}$) with ~ 60 SM event sensitivity and $\boldsymbol{S/B}$ ~ 1 can be performed at the CERN SPS with 5 × $\boldsymbol{10^{19}}$ pot**

AFTER: Fixed-target experiment using LHC beams

Gas-jet target, wire target, or crystal

pp	pA	PbA
$\mathcal{O}(10\ \mathrm{fb}^{-1}\mathrm{yr}^{-1})$	$\mathcal{O}(0.1-1\ \mathrm{fb}^{-1}\mathrm{yr}^{-1})$	$\mathcal{O}(1-50\ \mathrm{nb}^{-1}\mathrm{yr}^{-1})$

4 decisive features

- accessing the high x frontier $\quad [|x_F| \equiv \frac{|p_z|}{p_{z\,\max}} \to 1]$
- achieving high luminosities,
- varying the atomic mass of the target almost at will,
- polarising the target.

3 physics cases

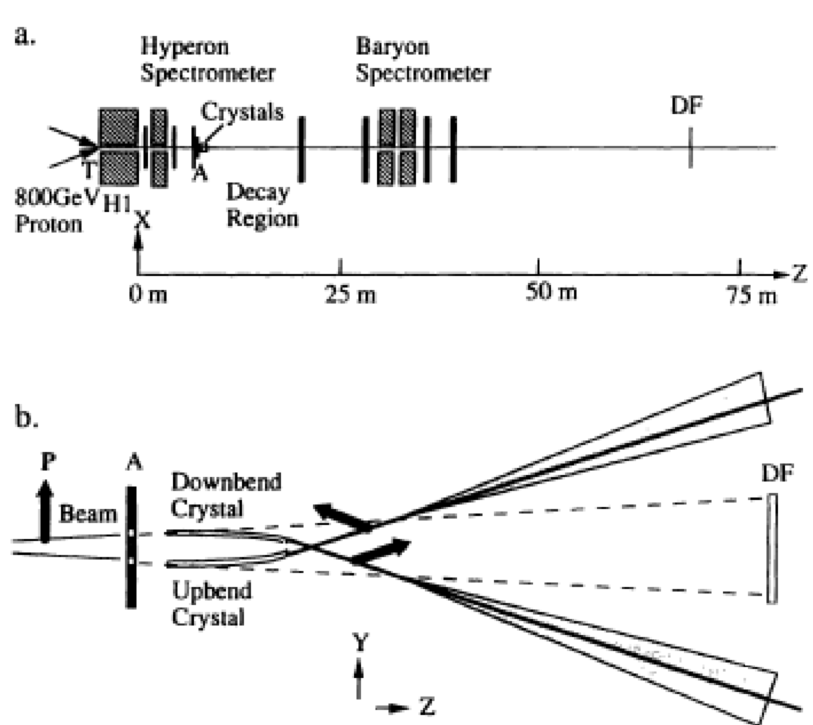
- High-x gluon, antiquark and heavy-quark content in the nucleon & nucleus
- Transverse dynamics and spin of gluons inside (un)polarised nucleons
- Heavy-ion physics between SPS & RHIC energies towards large rapidities

Spin precession in a bent crystal channel

E761 Collaboration. Measurement of the Σ+ magnetic moment - 1

VOLUME 69, NUMBER 23 PHYSICAL REVIEW LETTERS 7 DECEMBER 1992

First Observation of Magnetic Moment Precession of Channeled Particles in Bent Crystals



Proton (800GeV/c) + Cu → Σ^+ n particles

$\Sigma^+ \rightarrow p\,\pi^0$

As illustrated in Fig. 1, a vertically polarized Σ^+ beam [14] was produced by directing the Fermilab Proton Center extracted 800-GeV/c proton beam onto a Cu target (T). The resulting Σ^+ were produced alternately at a +3.7- or −3.7-mrad horizontal targeting angle relative to the incident proton beam direction. This allowed the polarization direction to be periodically reversed. The mean

The two bending crystals. Each crystal precess the channelled particle's spin in opposite direction

±20% measurement $\mu(\Sigma^+)$

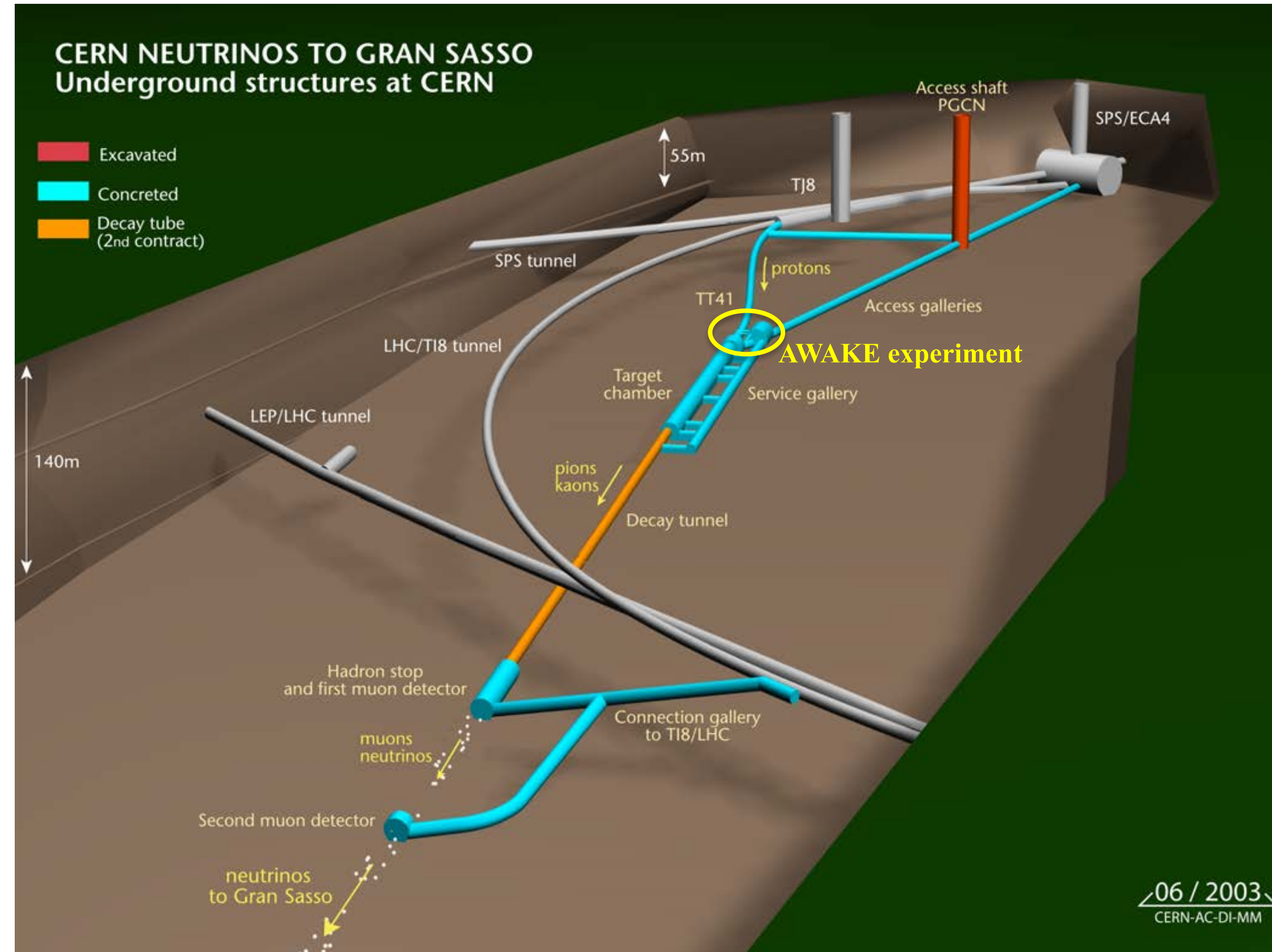
The deflection of the channeled particles was measured to be $\omega = 1.649 \pm 0.043$ and -1.649 ± 0.030 mrad for the up- and down-bending crystals, respectively. For 375-GeV/c Σ^+ this corresponds to an effective magnetic field of $B_x \approx 45$ T in the crystals. The magnetic moment [6] of the Σ^+ should precess by $\varphi \approx 1$ rad in such a field.

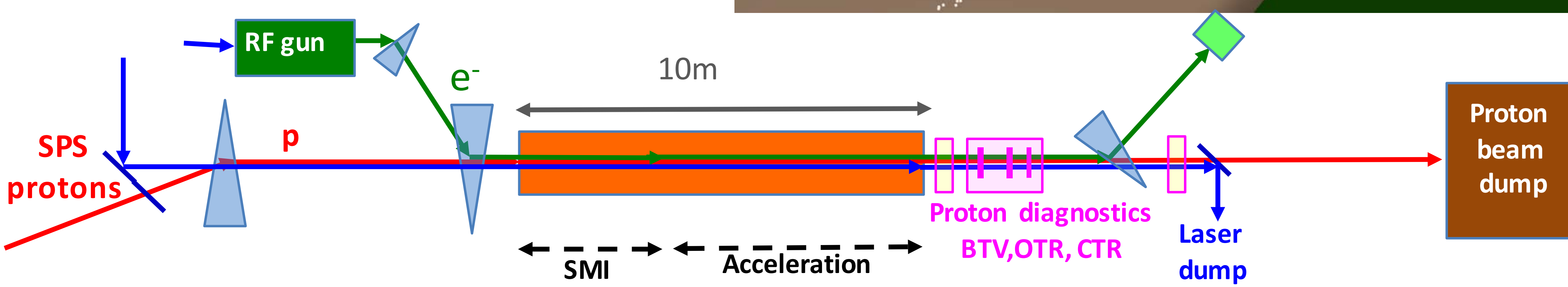
1/4000 channeled; rest made background

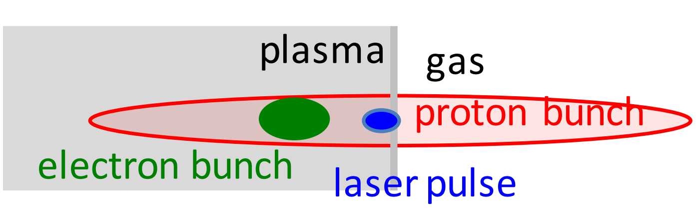
What would $\mu(\Lambda_c)$ teach us?

AWAKE: proton driven plasma wakefield experiment

- Demonstration experiment to show effect for first time and obtain *GV/m* gradients.
- Use *400 GeV* SPS proton bunches with high charge.
- To start running this year and first phase to continue to LS2.
- Apply scheme to particle physics experiments leading to shorter or higher energy accelerators.







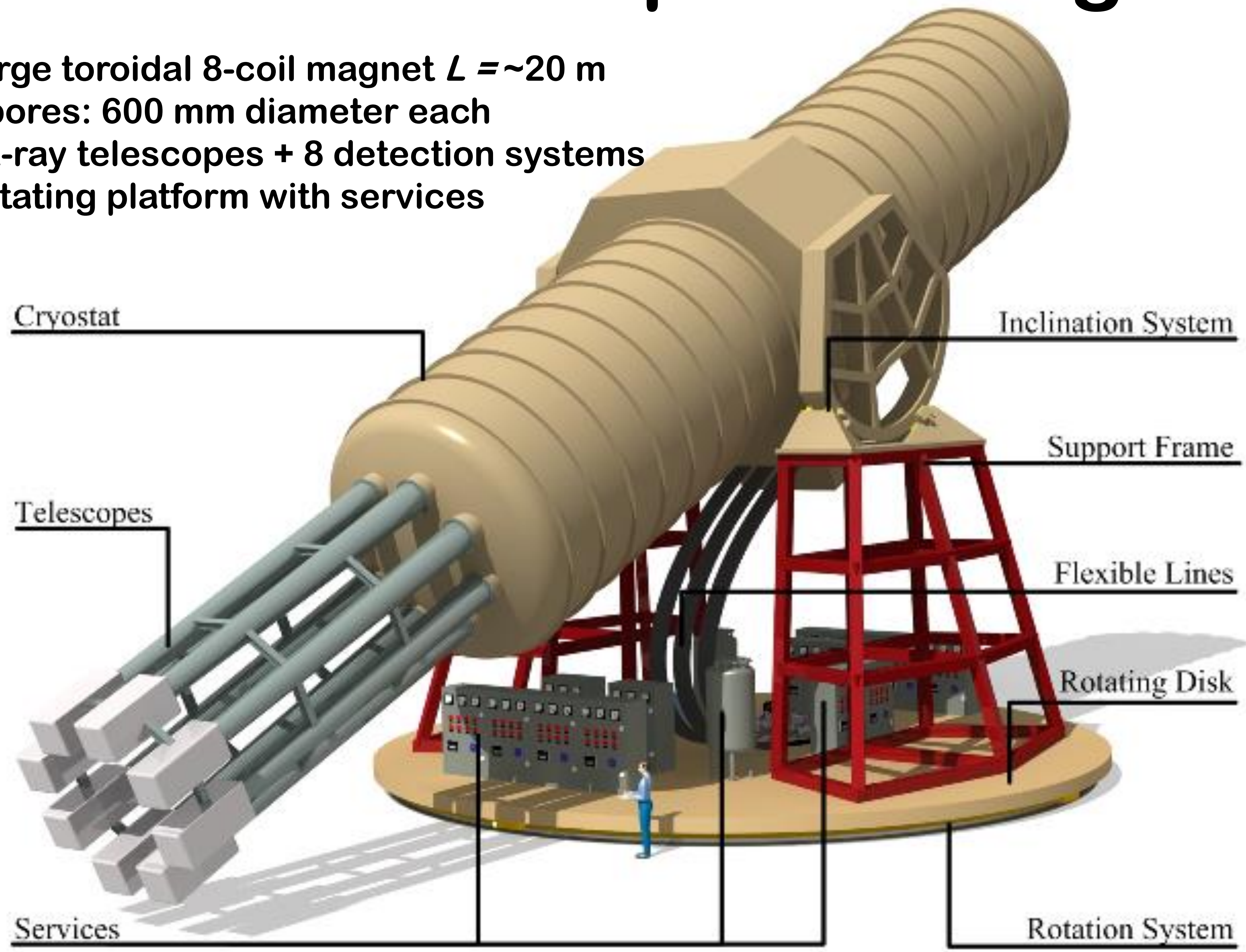
?? Increase NA64 e^- flux × 1000??

New Experimental Ideas

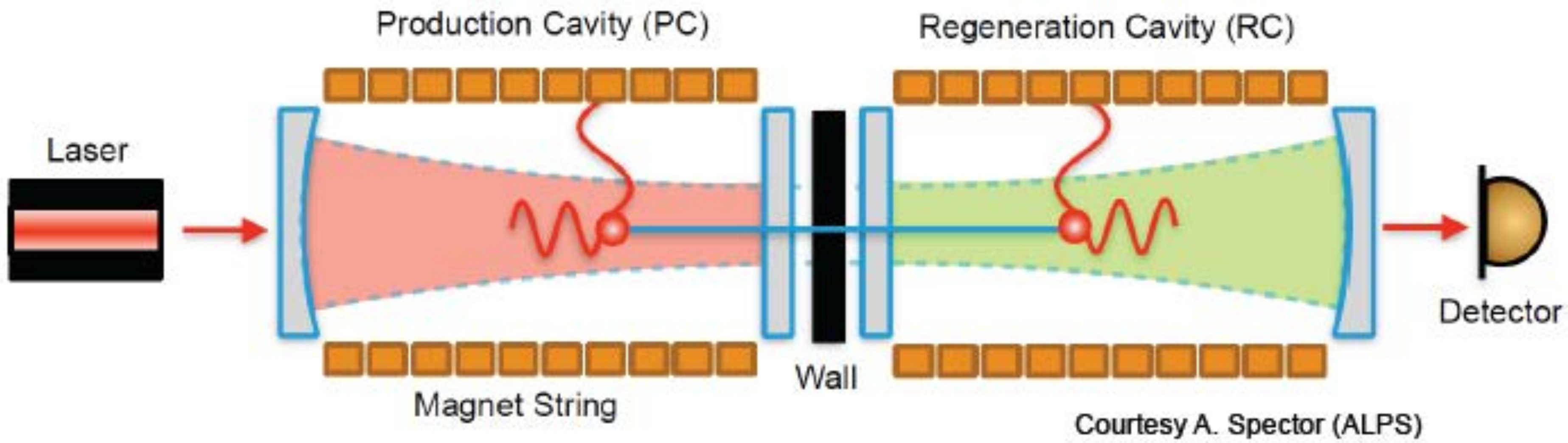
I. G. Irastorza · *International Axion Observatory*
G. Cantatore · *Advanced KWISP: membrane force sensors*
A. Lindner · *Light shining through a wall*
C. Galbiati · *DARKSIDE*

IAXO – Conceptual Design

- Large toroidal 8-coil magnet L = ~20 m
- 8 bores: 600 mm diameter each
- 8 x-ray telescopes + 8 detection systems
- Rotating platform with services



SNR = 10^4 × CAST; R&D, TDR encouraged



Ingredients for an “ALPS III” experiment

“ALPS III” sketch based on the following assumptions:

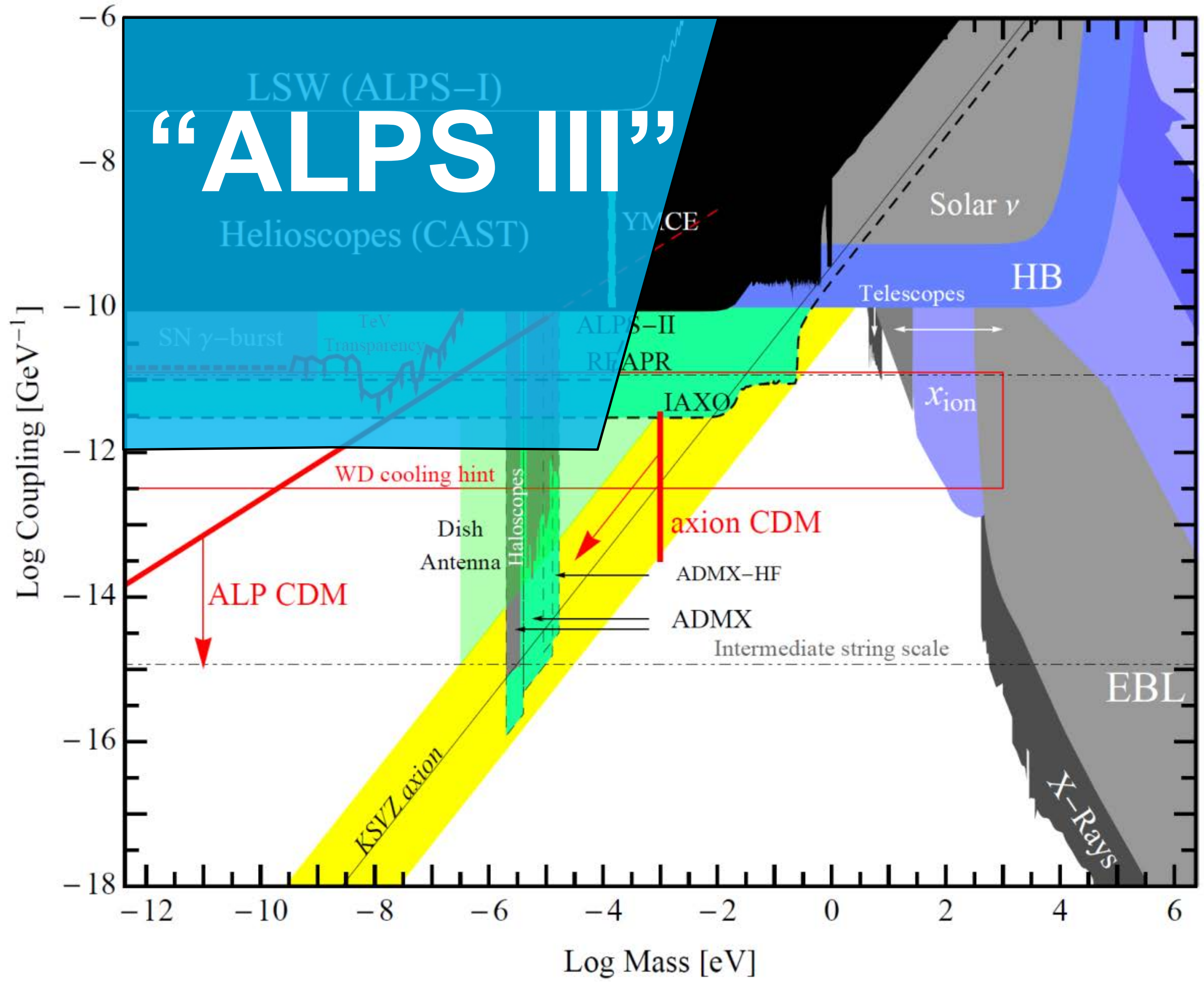
- Magnetic field strength: 13 T
- Magnetic length: 426 m
- Light wavelength: 1064 nm
- Circulating light power: 2.5 MW
  Photons against the wall: $1.4 \cdot 10^{25}$ s^{-1}
- Power built-up behind the wall: 10^{5}
- Detector sensitivity: 10^{-4} s^{-1}

- **Resulting sensitivity for $g_{a\gamma}$:**
  $1 \cdot 10^{-12}$ GeV^{-1} for $m < 0.06$ meV

“ALPS III” in context

“ALPS III”

- would dramatically increase the sensitivity for purely laboratory based experiments searching for axion-like particles.
- would surpass even IAXO for very low mass ALPs.
- would definitely probe astrophysics hints for ALPs.
- would probe “dark matter” ALPs.
- would perfectly complement IAXO!

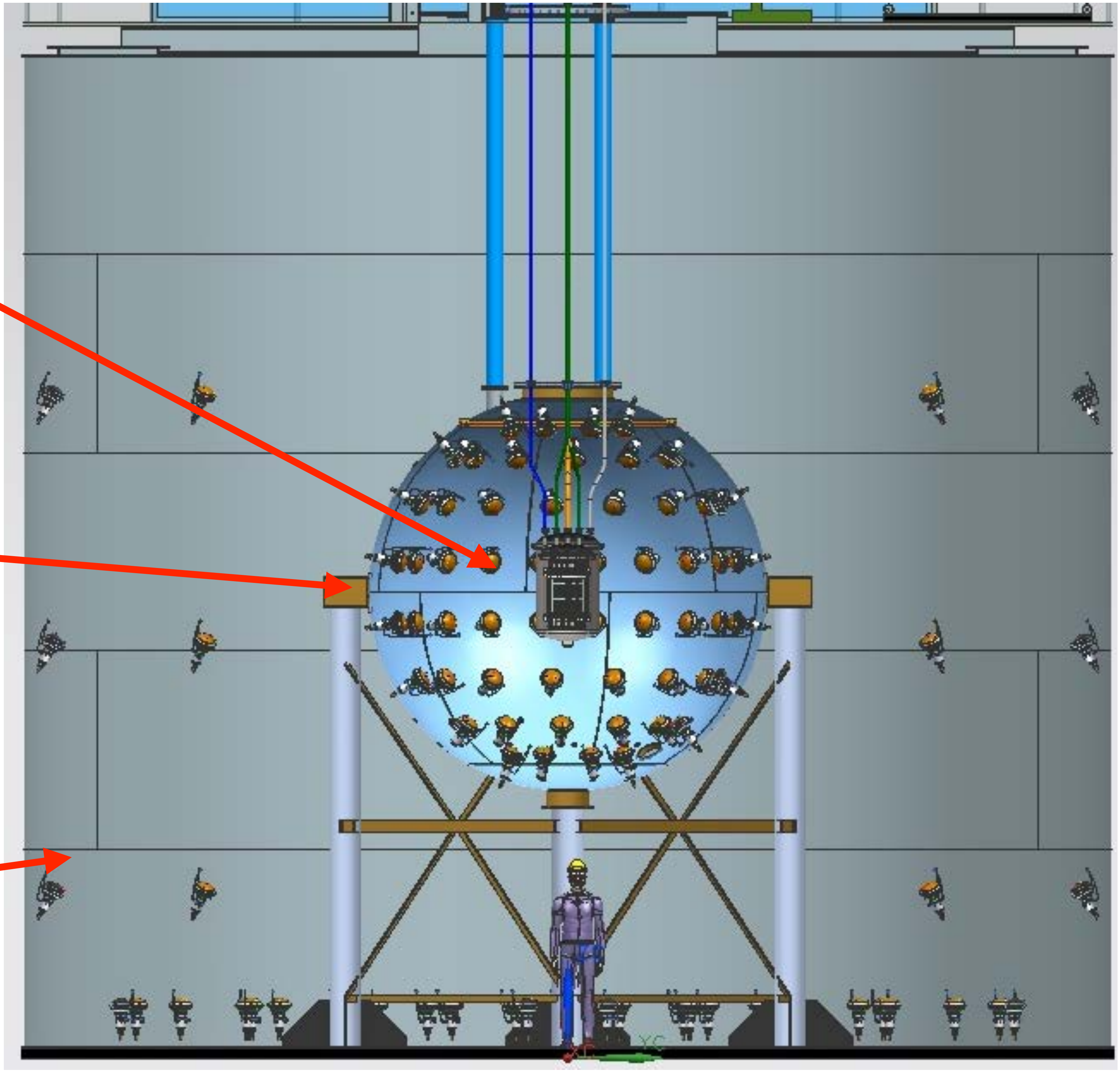


DARKSIDE: zero background dark-matter search

Liquid Argon TPC
153 kg ^{39}Ar-Depleted
Underground Argon
Target

4 m Diameter
30 Tonnes
Liquid Scintillator
Neutron Veto

10 m Height
11 m Diameter
1,000 Tonnes
Water Cherenkov
Muon Veto



Next steps:
Form working groups
Work
Solicit new ideas
Prepare Yellow report(s) … 2018
Present to European Strategy Update